The Influence of Office Furniture on the Air Movement in a Mixing Ventilated Room

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The Influence of Office Furniture on The Air Movements in a Mixing Ventilated Room

June Richter Nielsen

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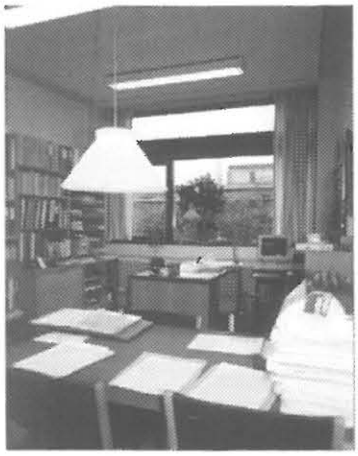
The Influence of Office Furniture on The Air Movements in a Mixing Ventilated Room



June Richter Nielsen

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The Influence of Office Furniture on the Air Movements in a Mixing Ventilated Room

June Richter Nielsen

This thesis has been made from July 1995 to June 1998 and it has been supervised by Professor Dr. Peter V. Nielsen and Associate Professor Dr. Kjeld Svidt, Aalborg University, Denmark.

ABSTRACT
Isothermal and thermal experiments and simulations form the basis of the investigations in this thesis. It is mainly the isothermal case that is studied. The examinations concern how normal office furniture influences the air movements in a mixing ventilated room. Especially, the jet under the ceiling, the maximum velocity in the occupied zone and the momentum flow through the room are studied.

The experiments are carried out with three types of inlets: a 2-dimensional slot inlet, a 3-dimensional slot inlet and two radial slots with swirl. The simulation of the first mentioned is 2-dimensional whereas the two last-mentioned inlets are simulated 3-dimensional. In the isothermal simulations a furniture volume is used to represent the physical furniture and in the thermal case a furniture volume together with a volume source is used.

The investigations of the isothermal experiments and simulations show that the jet under the ceiling is insignificantly influenced by the normal office furniture. The maximum velocity in the occupied zone is reduced by the furniture and this reduction is dependent on the total length of the furniture in the main flow direction. When the total length of the furniture increases the maximum velocity decreases. The momentum flow through the room is also reduced by the furniture. The reduction in momentum flow is decreased when the size of the furniture is small compared to the length of the room.

In the thermal experiments and the corresponding simulations the jet under the ceiling is affected by the furniture and by the heat load. The velocity decay and the width of the jet are both increased. The maximum velocity in the occupied zone is increased by the furniture with a thermal load. The changes in the air movements in the room are partly caused by the furniture and partly by the themal forces in the room. The thermal case needs more investigation because only two experiments and the corresponding simulations are the base of the investigations.

Aalborg University, Denmark
Department of Building Technology and Structural Engineering

Ph.D. Thesis, June 1998

Kontormøblements påvirkning af luftstrømningerne i et opblandingsventileret lokale

June Richter Nielsen

Denne afhandling er lavet i perioden fra juli 1995 til juni 1998, og professor Dr. Peter V. Nielsen og forskningslektor Dr. Kjeld Svidt, Aalborg Universitet, har været vejledere på afhandlingen.

RESUME

Isoterme samt termiske eksperimenter og simuleringer danner grundlaget for analysen i denne afhandling. Hovedvægten er lagt på de isoterme eksperimenter og simuleringer. Undersøgelserne omhandler, hvorledes typisk kontormøblement påvirker luftstrømningerne i et opblandingsventileret rum. Især er indblæsningsstrålen under loftet, maksimalhastigheden i opholdzonen og bevægelsesmængdestrømmen gennem lokalet af interesse.

Eksperimenterne er udført med tre forskellige indblæsningsarmaturer: en 2-dimensional spalte, en 3-dimensional spalte og to hvirveldiffusere. Simuleringen af førstnævnte er 2-dimensional, og de to andre indblæsningsarmaturer er simuleret 3-dimensionalt. I de isoterme simuleringer er der benyttet et møbelvolume i stedet for det fysiske møblement, og i de termiske simuleringer er møbelvolumet anvendt sammen med en volumenkilde.

Analysen af de isoterme eksperimenter og simuleringer viser, at indblæsningsstrålen under loftet er ubetydelig påvirket af det typiske kontormøblement. Maksimalhastigheden i opholdszonen reduceres af møblerne, og reduktionen er afhængig møblernes totale længde i hovedstrømningsretningen. Jo større den totale længde af møblerne er, jo mere reduceres maksimalhastigheden. Bevægelsesmængdestrømmen gennem lokalet er også reduceret af møblementet. Denne reduktion mindskes, når møblementets størrelse er lille i forhold til rummets længde.

I de termiske eksperimenter og de tilsvarende simuleringer er indblæsningsstrålen under loftet påvirket af møblementet samt af varmekilderne. Hastigheden er reduceret, og strålens bredde kan blive øget. Maksimalhastigheden i opholdszonen er øget af møblementet med en varmebelastning. Ændringerne af luftbevægelserne i rummet skyldes dels møblementet og dels de termiske strømninger i rummet. Det termiske tilfælde behøver yderligere undersøgelser, da kun to eksperimenter og de tilsvarende simuleringer indgår i analysen.

Aalborg Universitet
Instituttet for bygningsteknik

Ph.D. afhandling, juni 1998

Preface

This thesis is submitted in accordance to the conditions for attaining the Danish Ph.D. degree and it represents the end of my Ph.D. study at Aalborg University, Department of Building Technology and Structural Engineering. The research project has been carried out from July 1995 to June 1998.

The Ph.D. study has been supervised by Professor Dr. Peter V. Nielsen and Associate Professor Dr. Kjeld Svidt and I would like to express my gratitude for their guidance and advices.

My thanks also extend to Professor Dr. U. Renz and D. Müller and the rest of the staff at the Lehrstuhl für Wärmeübertragung und Klimatechnik at the RWTH in Aachen, Germany, for their hospitality and support during my stay.

I would like to thank colleagues and members of the technical staff for their valuable assistance during the study. I would especially like to thank C.E. Hyldgård for assistance in the laboratory, B.J. Kjærgaard for linguistic support and E. Bjørn for passing remarks on the work.

Finally, I will thank my family and friends for their patience and support.

June Richter Nielsen

June 1998

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1 Introduction

Nowadays many people spend the greater part of their time indoors /3/, /7/, /39/ and /42/. Therefore, it is of vital importance that the indoor climate is satisfactory. The term "indoor climate" covers the aspects of the thermal environment and the air quality that affects the comfort, the health and the safety of the occupants. Included could also be, e.g. the acoustics, the lighting and the colours of the room. Hereby, the indoor climate is influenced by many factors. The main goal is to provide an environment where the factors are combined so that comfort and well-being arises.

Several factors influence the feeling of thermal comfort and the six most important factors are: the metabolic rate, the clothing insulation, the radiation temperature, the air temperature, the humidity and the velocity of the air /7/, /8/, /9/, /15/ and /21/. The first two factors are determined by the function of the room whereas the remaining four factors form the thermal indoor climate that must be adjusted so that thermal comfort is obtained. These factors cannot be determined one by one because it is the interrelation between them that is decisive for the feeling of thermal comfort. This interrelation is expressed by a comprehensive comfort equation produced by Fanger /12/. The thermal environment in a room is very difficult to adjust so that everyone present in the room is completely satisfied because the individual feeling of comfort varies from person to person.

The main objective when designing ventilated spaces is to create optimal thermal comfort. This is done by using the comfort equation so that the feeling of the thermal environment is neutral. Satisfying everybody in the room is not possible. The minimum value of dissatisfied is 5% and when designing the indoor climate in a room no more than approximately 10% of the occupants must be dissatisfied /7/, /10/ and /17/. Though thermal comfort is reached according to the comfort equation it is not guaranteed that the person actually is feeling neutral because local discomfort can arise. The local discomfort can be caused by asymmetric thermal radiation, a vertical temperature gradient or draught /7/, /9/, /11/, /13/, /15/, /17/, /27/, /30/, /35/, /41/ and /42/.

Draught is caused by undesired air movements where the air velocity is to high or/and the air temperature is to low. The feeling of draught is dependent on the other thermal conditions in the room, so that if the person is feeling too warm, the local cooling from a high air velocity will be easier accepted than if the person is feeling too cold. An air velocity of maximum 0.15 m/s is found appropriate for seated persons whereas moving people accept a higher air velocity /1/, /5/, /8/, /9/, /17/, /41/ and /43/. Variations in the air velocity increases the feeling of draught even if the average velocity is low /17/. These variations arise from, e.g. moving people, heat sources and cold surfaces. The maximum velocity of 0.15 m/s is often exceeded in rooms with mechanical ventilation because the ventilation system is designed in an insufficient way so that the supply air is too cold or the inlet velocity is too high /1/ and /41/. The consequences are that the air is inadequately distributed and inconvenience arises. The problems with draught are big and draught has been identified as one of the most annoying factors in offices /2/.

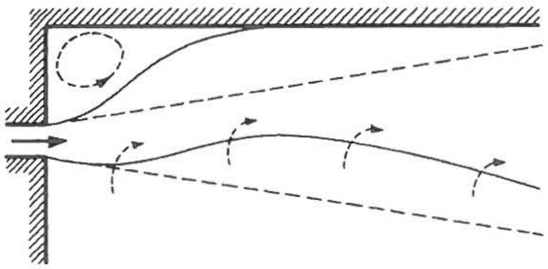
As described above many things are to consider when designing a good indoor climate. The optimum solution is that everybody in the room is completely satisfied but this is often difficult to accomplish. The objective is then to satisfy as many as possible and under all conditions. It is often so that under the most extreme conditions a higher number of dissatisfied has to be accepted due to financial reasons. As mentioned above draught is a serious problem in ventilated spaces due to increased air velocity caused by insufficiently designed ventilation. The following section describes some methods used for designing ventilation systems.

1.1 Ventilation

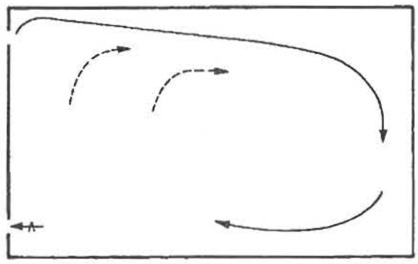
The main purpose of a ventilation system is to supply air to a room so that the occupants of the room are feeling comfortable. Creating a uniform thermal environment in a room is very difficult because the flow in the room varies with the function of the room /15/. This means that among other things does heat and lighting sources and furniture influence the air flow in the room /8/ and /11/. In addition the location and design of the inlet together with the geometry of the room can affect the air distribution /30/. As mentioned above it is very important that draught does not occur in the occupied zone of the room. Therefore, the magnitude of the velocity must be determined in the room, when the ventilation system is designed, so that the maximum velocity of 0.15 m/s is not exceeded in the occupied zone of offices. However, outside the occupied zone higher velocities can be accepted.

First, when a ventilation system is designed the principle of ventilation must be determined. There are two main principles of ventilation - displacement ventilation and mixing ventilation. In displacement ventilation the air is supplied in the occupied zone with a low velocity and a temperature lower than the air temperature. Convection due to heat sources in the room does then control the air movements in the room. In mixing ventilation the air is supplied outside the occupied zone and a recirculating flow is created. In the following only mixing ventilation will be described more closely because this type of ventilation is used in the investigations made in this thesis.

In a mixing ventilated room air is supplied outside the occupied zone and a jet is generated in front of the opening. Under isothermal conditions this jet, which is turbulent, will either continue into the room as a free jet or be attached to a surface as, e.g. the ceiling and by that form a wall jet. The wall jet often arises when the inlet is located close to the ceiling because the pressure distribution will attract the jet up under the ceiling (Coanda effect) (see figure 1.1 to the left). At the underside of the jet, air is entrained from the occupied zone and hereby a recirculating air movement in the room is produced (see figure 1.1 to the right). The location of the exhaust in the room is less important because the exhaust only influences the flow field close to it. /7/, /27/, /28/, /29/ and /30/.



The Coanda effect



The recirculating flow in a mixing ventilated room

Figure 1.1 *The creation of a wall jet due to the Coanda effect and the principle of mixing ventilation /7/.*

Under thermal conditions, the buoyancy will influence the air movements in the room. When the inlet temperature is higher than the exhaust temperature, both the Coanda effect and the buoyancy will influence the jet and in the worst case the supplied air never gets down into the occupied zone (thermal stratification). When the inlet temperature is below the exhaust temperature there is a risk of the jet being separated from the ceiling and thereby deflecting down into the occupied zone with a high velocity and a low temperature. This increases the probability of draught. The distance from the supply opening to the separation with the ceiling depends on the geometry of the supply opening, on the geometry of the room and on the location of the heat sources. If the heat source is located at the end wall opposite the inlet, the penetration depth is smaller than if the heat source is located at the same wall as the inlet. The thermal flow is characterized by the Archimedes number, Ar. If Ar is small, the flow will be almost isothermal whereas if Ar is large, the thermal forces will affect the flow in the room. /7/, /27/, /28/ and /30/

Under isothermal conditions, the velocity decay of the jet at the ceiling can be determined using different equations dependent on the used type of inlet. This description of the jet flow outside the occupied zone is very important because it forms the basis of the design methods for ventilation systems. However, the problem is that the equations are only valid if the jet is undisturbed. This means that when the jet is deflected by, e.g. hanging lamps or the end wall opposite the inlet, the actual conditions differ from the ones assumed in the equations. Therefore, the velocity in the occupied zone cannot be determined directly from these simple equations if the jet is disturbed. The design of the ventilation system can be made on the basis on, e.g. experiments, numerical simulations or from flow element theory (throw of an isothermal jet) where the first two methods can include a possible disturbance of the jet and the last method assumes an undisturbed jet. Furthermore, the latter method has a sufficient level of accuracy when it is used in a regular room. /7/, /27/, /28/ and /30/

The design method applying throw uses the velocity of the undisturbed jet at the ceiling at a distance corresponding to the length of the room, u_L, to determine the maximum velocity in the occupied zone, u_{rm}. It has been found that $u_{rm}/u_L \sim 0.7$ in case of a 2-dimensional wall jet. Figure 1.2 shows the location of u_L and u_{rm} in a room where the inlet is located in the end wall close to the ceiling. In a room with this type of inlet, the maximum velocity in the occupied zone is to be found in a distance of 0.5 L to 0.7 L from the inlet, where L is the length of the room. /7/, /27/, /28/, /29/ and /30/

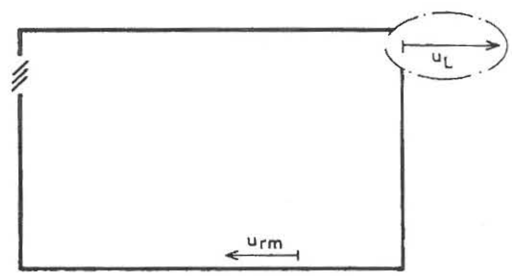


Figure 1.2 *The location of u_L and u_{rm} in a mixing ventilated room /28/.*

In case of thermal conditions, the maximum velocity in the occupied zone can be increased because the air flow in the room is changed. At increasing Archimedes number, the circulation in the room increases by which the maximum velocity in the occupied zone also increases. At the same time, the centre of the flow and by that the location of u_{rm} is displaced towards the middle of the room. /27/ and /30/

1.2 The Objectives of this Thesis

As described earlier, designing a ventilation system without having to do experiments or CFD (Computational Fluid Dynamics) simulations is possible when a regular room is used. The equations used for the design procedure are developed on the basis of experiments and simulations carried out in empty rooms. However, an empty room is very seldom the case because normally furniture and heat loads as for example persons are present in the room. That furniture or obstacles in the occupied zone do influence the air movements in the room has been shown by /16/, /22/ and /40/. The investigations made by the three authors mentioned above were all under isothermal conditions and both experimental and simulated results are used in the investigations.

In this thesis full scale experiments and CFD simulations form the basis of an investigation of the influence of normal office furniture on the air movements in a mixing ventilated room. The investigations are made under both isothermal and thermal conditions where the main stress is laid on the former. The experiments are carried out in two different rooms and three types of supply openings are tested. In the rooms a physical set-up with normal office furniture is made and the air flow is compared with the air flow found in the corresponding empty room. The physical set-ups are simulated and additional simulations are made. The simulations are both 2- and 3-dimensional where the 2-dimensional simulations are only under isothermal conditions and the 3-dimensional simulations are made under both isothermal and thermal conditions.

The thesis is divided into two major parts consisting of the isothermal case and the thermal case (chapter 2 and 3, respectively). Each part contains both experiments (chapter 2.1 and 3.1) and simulations (chapter 2.2 and 3.2). The investigations of the air movements in a furnished room are concerning the jet under the ceiling and the velocity level in the room where the maximum velocity in the occupied zone is of special interest. Furthermore, the influence from the furniture on the momentum flow in the room is studied. These topics are mainly chosen on the basis of other investigations made in this field.

/22/ and /40/ found under isothermal conditions that solid boxes influence the jet under the ceiling. The investigations are here extended to concern how normal office furniture in a room under both isothermal and thermal conditions influences the air flow in the upper part of the room. This is done for the isothermal case in chapter 2.3.1 and for the thermal case in chapter 3.

/16/, /22/ and /40/ all found under isothermal conditions that both solid boxes and normal office furniture reduce the velocity level in a room including the maximum velocity in the occupied zone. In this thesis this statement is tested and a method for the calculation of the maximum velocity in the occupied zone of a room with normal office furniture under isothermal conditions is developed. This is done in chapter 2.3.2 .

/22/ found that solid boxes in the room reduce the momentum flow and this subject is investigated more closely in the isothermal case with normal office furniture. This is done in chapter 2.3.3.

A general view of some of the isothermal investigations carried out in this thesis can be found in /23/, /24/, /25/ and /26/.

2 The Isothermal Case

In this chapter the isothermal experiments with furniture and the matching 2- and 3-dimensional, isothermal CFD simulations are described. The experiments are carried out using three different inlets in two different rooms. The inlets are a 2-dimensional slot inlet, a 3-dimensional slot inlet and two radial jets with swirl. In all the cases the principle of ventilation is mixing ventilation. The experimental conditions are simulated and further simulations are made with one inlet. The CFD simulations are made with the program Flovent.

The results are investigated and the influence from the furniture on the air movements in the room is analysed. The investigations are divided into three parts: the jet under the ceiling, the maximum velocity in the occupied zone and the momentum flow in the room where a method for the determination of the maximum velocity in the occupied zone of a furnished room is developed.

2.1 Experiments

The isothermal experiments are made in two different full-scale rooms located in Aalborg, Denmark, and in Aachen, Germany. In the room in Aalborg the inlet is a slot close to the ceiling that covers the one end wall of the room. Hereby, the inlet creates a 2-dimensional flow and the situation will in this thesis be called the 2-dimensional slot inlet. In this room three different set-ups with office furniture are made. In the room in Aachen two types of inlets are used on the same set-up of office furniture. One inlet is a slot in the ceiling close to the middle of the room and it has the width of the room. This inlet injects air into the room in two opposite directions so that both halves of the room get fresh air. The other inlet consists of two radial jets with swirl and they are placed with one in each half of the room. These two inlet types are in this thesis called the 3-dimensional slot inlet and the two radial jets with swirl, respectively.

The rooms, the inlets, the set-ups, and the flows in the rooms are described in details in the following. Comparison between the empty and the furnished room is made and the results from the different set-ups are also compared. The comparison is concentrated on the velocity level in the room, the shape of the velocity profile, the velocity decay at the ceiling and the maximum velocity in the occupied zone.

2.1.1 Experiments with the 2-dimensional Slot Inlet

The room used in the experiments with the 2-dimensional slot inlet is an insulated full-scale room with the dimensions (LxWxH) 5.40x3.60x2.50 m. The inlet and the exhaust are at the same end wall where the inlet is close to the ceiling and the exhaust is close to the floor. The inlet is a 0.01 m high slot that covers the whole width of the room. It is placed in a box of 0.25x0.25 m and is located 0.023 m from the ceiling (see figure 2.1).

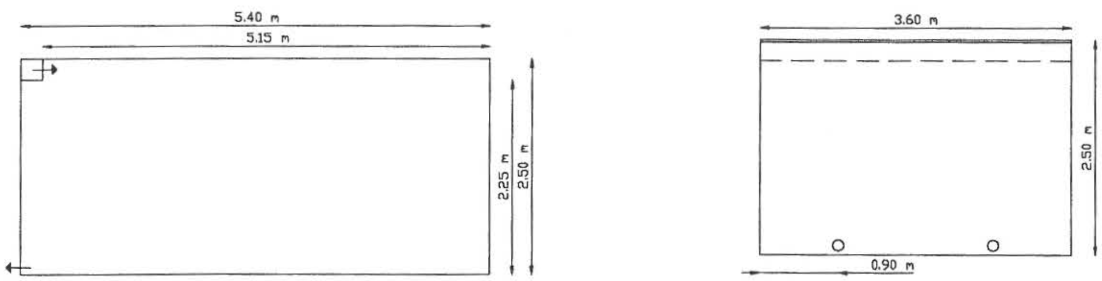


Figure 2.1 *The full-scale room used in the experiments (to the left) and the location of the inlet and the exhaust at the end wall (to the right).*

The inlet is made this way to build a 2-dimensional wall jet. The exhaust consists of two holes each having a diameter of 0.125 m and they are 0.05 m above the floor.

In all the experiments made with the 2-dimensional slot inlet, the inlet velocity is 3.47 m/s.

In the room two hanging lamps are present. Figure 2.2 shows the location and the size of the lamps.

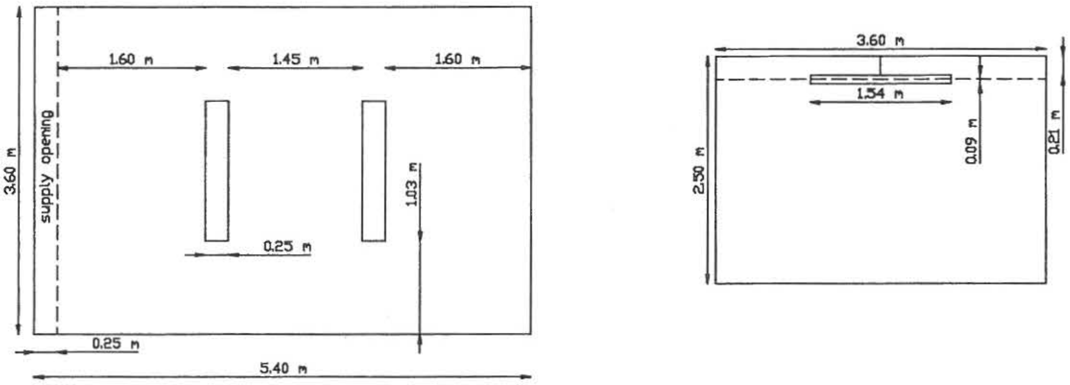


Figure 2.2 The location and the size of the hanging lamps.

The further drawings and the simulations are without the lamps because their influence on the inlet jet is negligible (see appendix A).

2.1.1.1 Measuring Equipment

In the experiments made with the 2-dimensional slot inlet mainly velocities are measured. Temperature is only measured in the inlet and in the exhaust to make sure that isothermal conditions are present. Furthermore, the inlet velocity is frequently checked by measuring the flow in the inlet.

The velocity measurements are made in the centre line of the room 1.00, 2.00, 3.00 and 4.00 m from the supply opening. Furthermore, 2.00 m from the inlet measurements are made per 0.60 m across the room to check the inlet jet for inequality (see figure 2.3).

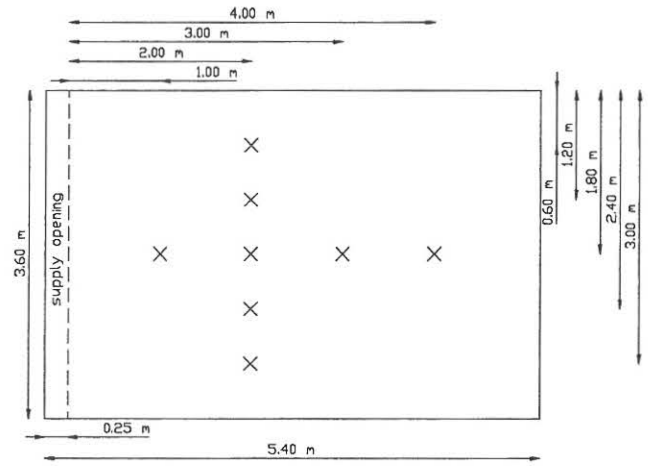


Figure 2.3 The points in the room where velocity is measured (×).

The measurements are made with a low velocity flow analyser type 54N10 from Dantec. The Dantec 54N10 is a microprocessor-based anemometer with an omnidirectional velocity sensor that is fully temperature compensated /6/. The instrument works on the basis of the hot-sensor anemometer principle that utilizes the relationship between heat transfer and flow velocity /6/.

In the experiments 18 transducers are connected to the instrument and measurements are made in 36 heights between the floor and the ceiling (see figure 2.4).

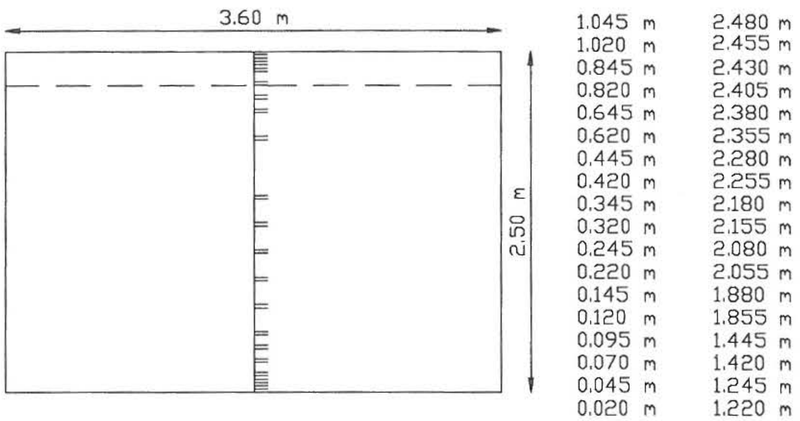


Figure 2.4 *The heights where velocity is measured.*

The measuring points are closer together in the floor area and in the ceiling area because the maximum velocity at the floor and at the ceiling, respectively, is to be found close to the wall. The measurements are made with an integration time of 10 minutes which is found appropriate to avoid the fluctuations of the velocity.

2.1.1.2 The Flow in the Empty Room

The air movements in the empty room with the 2-dimensional slot inlet is of interest because this condition is used as a reference to the measurements in the furnished rooms. The reason for doing this is, that the used theory to determine the air flow in a room is based on the assumption that the room is empty. Hereby, the air flow conditions in the empty room can be estimated without making experiments or simulations.

The overall air movements in the room are studied by adding smoke to the air in the room. Hereby, it is seen that the jet follows the ceiling to the end of the room and here it deflects down into the occupied zone of the room. The return flow moves along the floor and by that the flow in the room makes a circular movement (see figure 2.5) which also was expected /7/, /27/, /28/, /29/ and /30/.

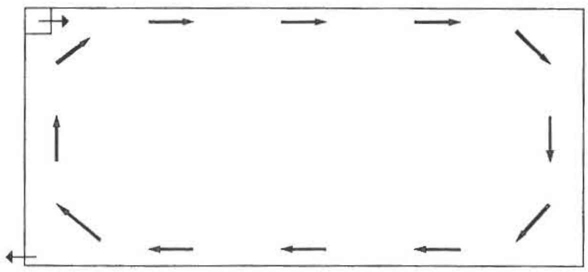


Figure 2.5 *The flow in the empty room.*

During the velocity measurements made in the empty room some problems arose because the flow at the ceiling was not steady 2-dimensional. The inlet creates a 2-dimensional wall jet (see figure 2.6 to the left) but occasionally the flow moves to a corner (see figure 2.6 to the right). The deviation from the complete 2-dimensional jet only occurs in the half of the room opposite the inlet.

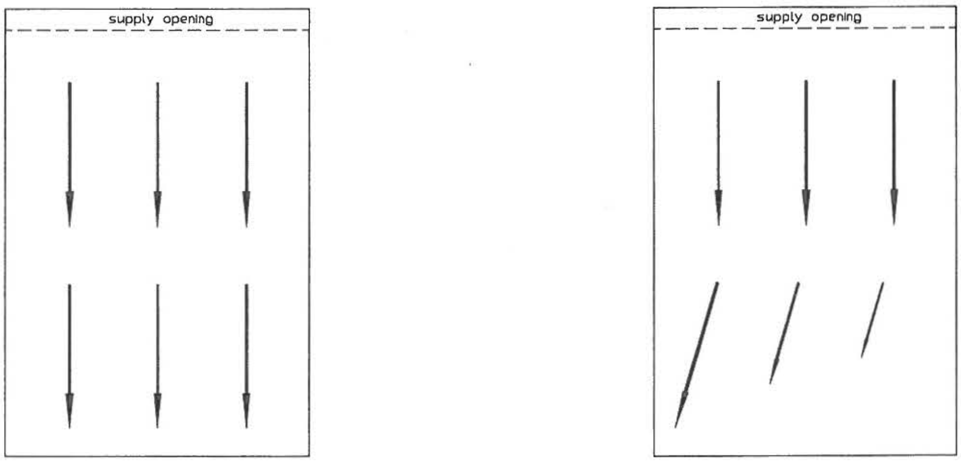


Figure 2.6 *The room seen from above where the flow at the ceiling is steady 2-dimensional to the left and to the right, the air moves towards a corner in the last half of the room. This corner is not always the same.*

Because the flow does not move towards a corner with a fixed interval of time, several velocity measurements are made at the same location in the room. The measurements representing the 2-dimensional flow are then selected so that the criterion for velocity decay at the ceiling is fulfilled /7/, /27/, /30/ and /36/. In the experiments with office furniture the wall jet does not show this behaviour.

The velocity measurements and the analyses of them are presented in the comparison with the results found in the experiments with a furnished room (see section 2.1.1.5).

2.1.1.3 Three Set-ups with Office Furniture

In the room with the 2-dimensional slot inlet three different set-ups are made where the same office furniture is used in all the cases. The furniture consists of two desks, two computers, two monitors, two computer tables and two cylinders where the latter are used instead of two real persons. The dimension of one cylinder is (H×D) 1.00×0.40 m. The following figure shows the measures of the used furniture.

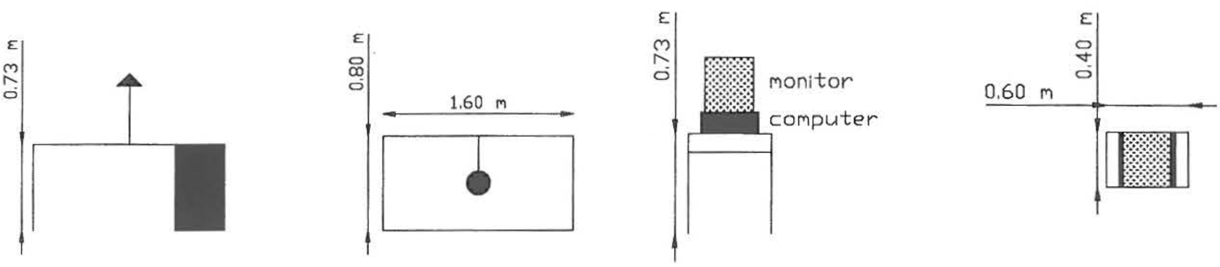


Figure 2.7 *The desk with a reading lamp (the two left) and the computer table with a computer (L×W×H) 0.415×0.40×0.16 m and a monitor (L×W×H) 0.35×0.40×0.40 m on the top (the two right).*

Common for the three set-ups with office furniture is symmetry about the centre line of the room and that the furniture is only present in the half of the room opposite the inlet opening. The set-ups are chosen so that the space requirements for an office are fulfilled /34/. The furniture is placed here to disturb the flow in the room the most (the flow has its maximum velocity in the occupied zone in this area /7/, /27/, /28/ and /30/). The three set-ups can be seen in figure 2.8.

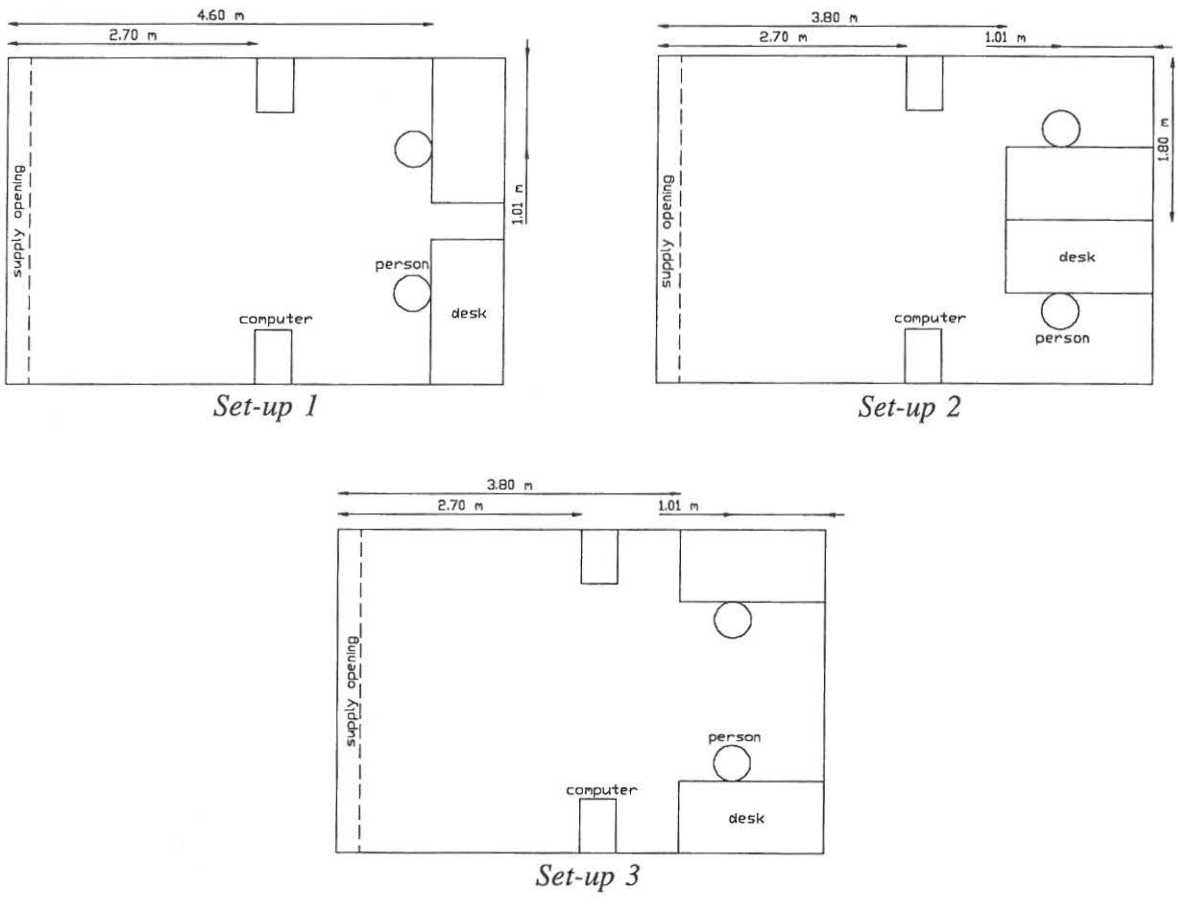


Figure 2.8 *The three experimental set-ups with office furniture.*

In the experimental set-up 2 no velocity measurements are made 4.00 m from the inlet because the desks are covering the measuring point (see figure 2.3).

2.1.1.4 The Flow in the Room with Office Furniture

The analysis of the air movements in the room with the 2-dimensional slot inlet when office furniture is in the half of the room opposite the inlet opening consists of two parts. The first part is an overall description based on the visual observations and the second part is the velocity measurements and the investigation of these. The latter part is described in the next section (section 2.1.1.5) where comparisons with the measurements in the empty room are made.

Like in the empty room smoke is added to the air to visualise the air movements in the room when office furniture is present. The following figure shows the air movements in the room with the three experimental set-ups.

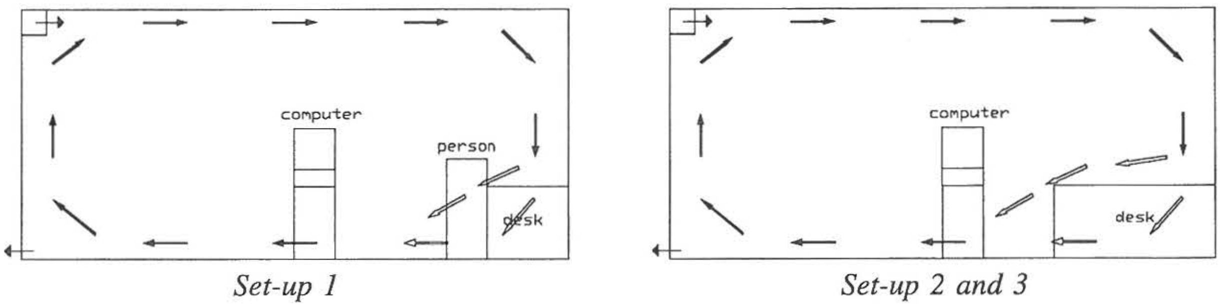


Figure 2.9 *The flow in the room when office furniture is present. Set-up 2 and 3 are presented in one drawing.*

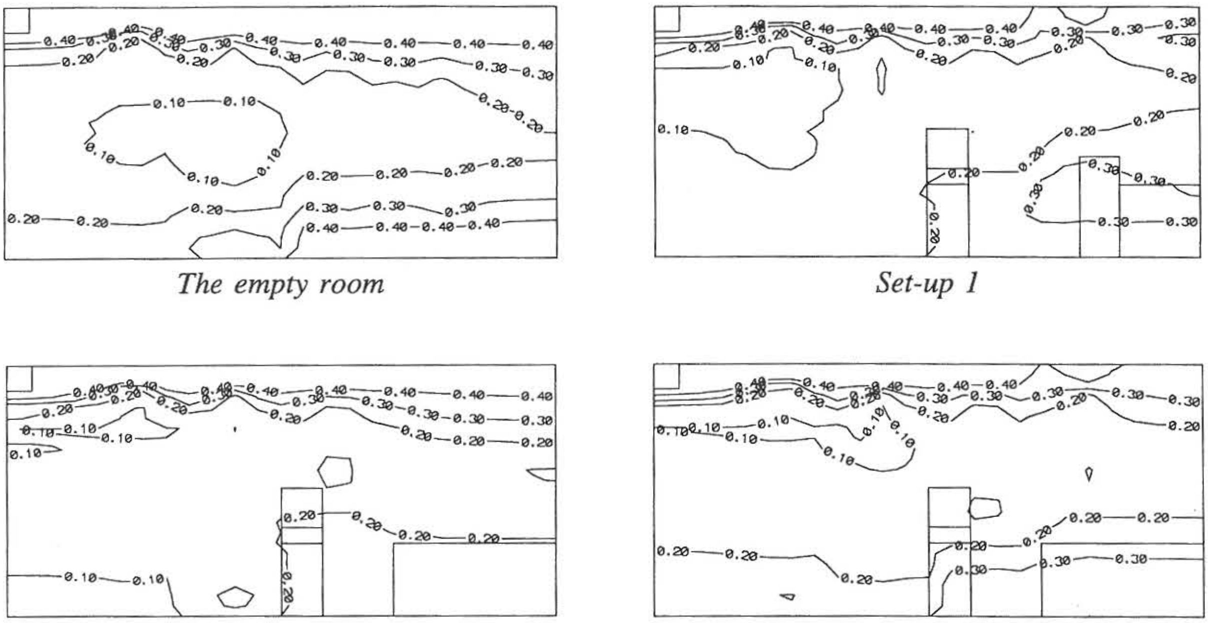
In all three set-ups the jet follows the ceiling to the end of the room and here it deflects down into the occupied zone which is the same as was found in the empty room (see figure 2.5). A difference between the empty room and the furnished room occurs when the jet in the furnished room reaches the desks that are standing at the end wall. Where the desks are present, the jet deflects over them instead of continuing to the floor like in the empty room. However, the jet does reach the floor in the desk area because the air after moving over the desks falls down to the floor. Where the desks not are present, the jet still continues to the floor like in the empty room. In the experimental set-up 1 only a very little part of the jet can reach the floor at the end wall whereas a bigger part of the jet reaches the floor at the end wall in experimental set-up 2 and 3. This difference is caused by the direction of the desks (see figure 2.9). Still though, the main flow direction in the room is maintained because the desks only cause a local disturbance to the flow.

2.1.1.5 Differences Between the Empty and the Furnished Room

In order to see the influence on the air movements in the room caused by the office furniture, other than visually, several things can be investigated. Here is chosen to concentrate on the overall velocity level in the room, the shape of the velocity profile, the development and influence on the jet under the ceiling and finally the maximum velocity in the occupied zone.

The overall velocity level is drawn from the velocity measurements and afterwards interpolation between the velocities is made with the method Kriging[1]. At all the walls the velocity is 0.0 m/s but this is not used in the interpolations because the distance from the end wall to the nearest point of measurement is to big to get a realistic representation of the results. The following figure 2.10 shows the velocity level in the empty room and in the rooms with the three experimental set-ups.

[1] Kriging uses geostatistical techniques to calculated the autocorrelation between data points and produce a minimum variance unbiased estimate.



The empty room

Set-up 1

Set-up 2

Set-up 3

Figure 2.10 *The velocity level in the centre line of the empty room and in the three furnished rooms. Only velocities lower or equal to 0.40 m/s are shown.*

By comparing the three furnished rooms with the empty room it is seen that the velocity level under the ceiling is alike and that the velocity at the floor is lower in the furnished room than in the empty room. As seen by adding smoke to the air, the air movements in the lower part of the room are different when furniture is present in the room and the air does not make so clear a circular movement as in the empty room. The reason that a zone with 0.30 m/s does not occur in set-up 2 is that velocity measurements are not made 4.00 m from the inlet because the desks are covering the measuring point. Judging from the visualization with smoke the zone with 0.30 m/s is also present in set-up 2.

As it is seen from figure 2.10, the velocity level in the furnished room is different from the one found in the empty room and especially in the lower part of the room. Therefore, it is investigated how the influence is on the velocity profiles measured in the room (see figure 2.12 to 2.15). The velocities are drawn positive when the flow has the same direction as the jet under the ceiling (see figure 2.11).

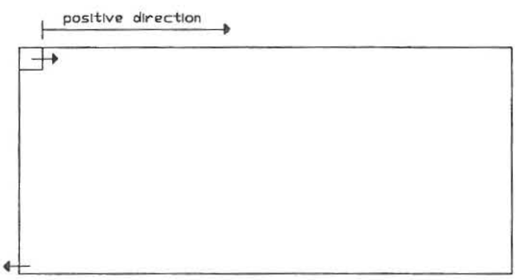


Figure 2.11 *Definition of the positive direction of the velocities.*

The very low velocities measured are partly turbulent fluctuations because due to the measuring equipment it is not possible to seperate velocity and turbulence.

In figure 2.12 to 2.15 the velocity profiles found in the empty room are compared with the ones found in the three furnished rooms. The velocity profiles are measured 1.00, 2.00, 3.00 and 4.00 m from the inlet.

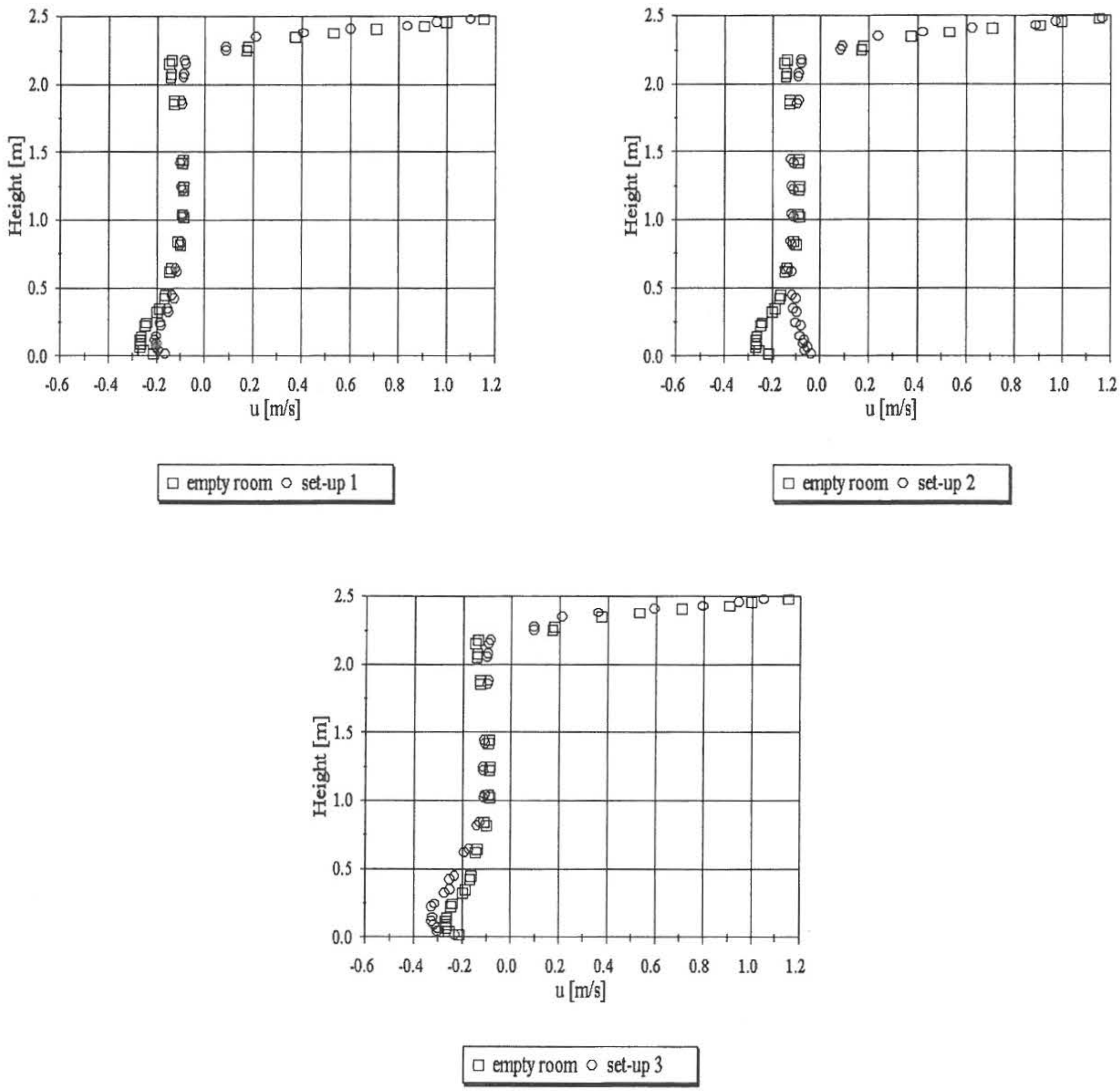


Figure 2.12 *The measured velocity profiles 1.00 m from the inlet in the empty room and in the three furnished rooms.*

In figure 2.12 it is found that 1.00 m from the inlet there is almost no influence from the furniture on the air flow in the room. It is only close to the floor (lower than 0.50 m) that the velocities are affected by the furniture and the velocities are decreased compared with the empty room. Here especially set-up 2 shows a deviation and it is caused by the desks in the centre-line of the room where also the measurements are made (see figure 2.3).

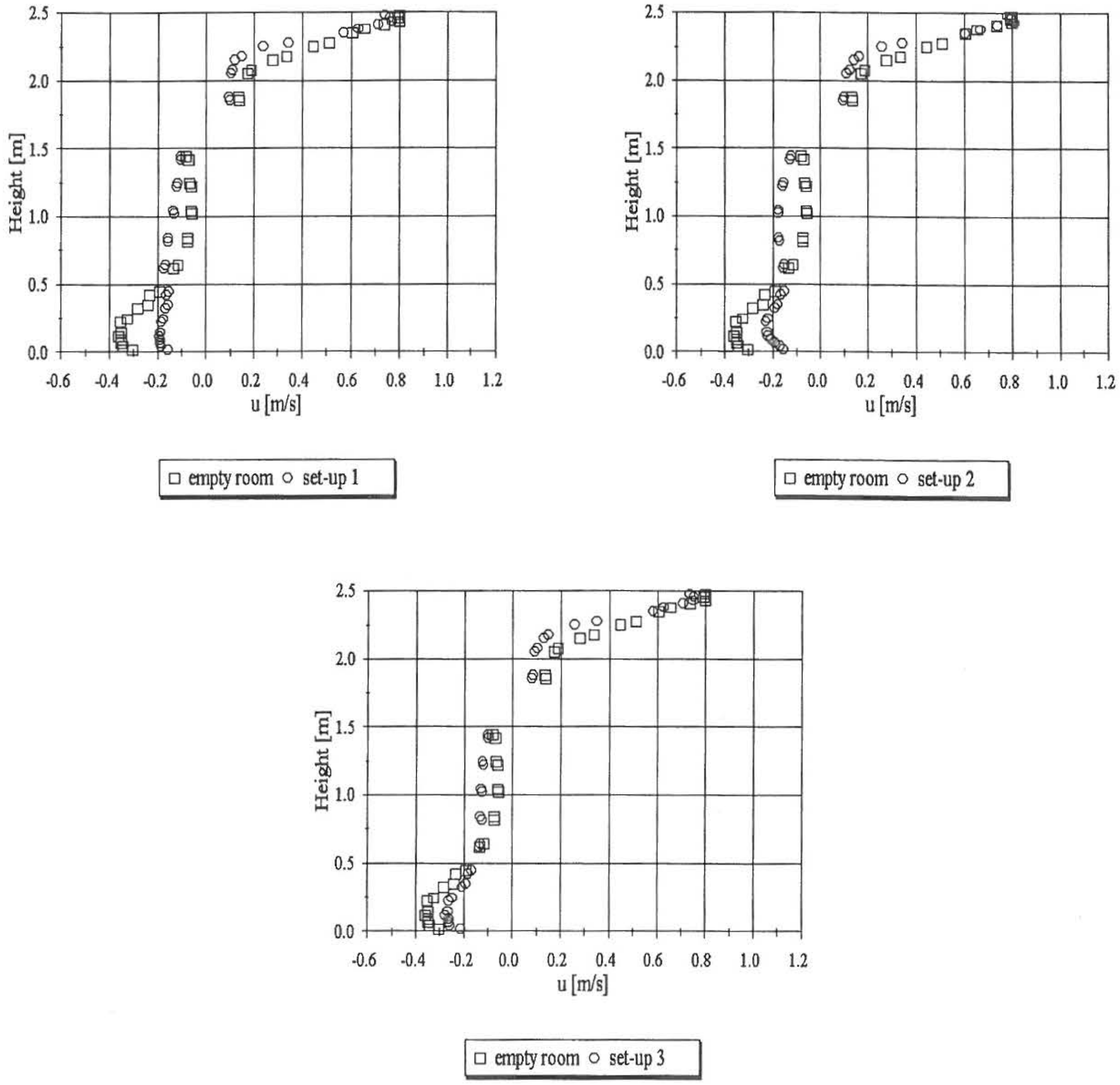


Figure 2.13 *The measured velocity profiles 2.00 m from the inlet in the empty room and in the three furnished rooms.*

The velocity profiles 2.00 m from the inlet in the three experiments with office furniture are determined as the average value of the five measurements made at this distance (see figure 2.3). In the empty room the representative velocity profile is used (see section 2.1.1.2). In figure 2.13 it is seen that the difference between the empty room and the furnished room has increased compared with 1.00 m from the inlet (figure 2.12). Now the air velocity in the middle of the room is also slightly affected by the furniture and the velocity is increased compared with the empty room. Hereby, a deformation of the velocity profile is indicated.

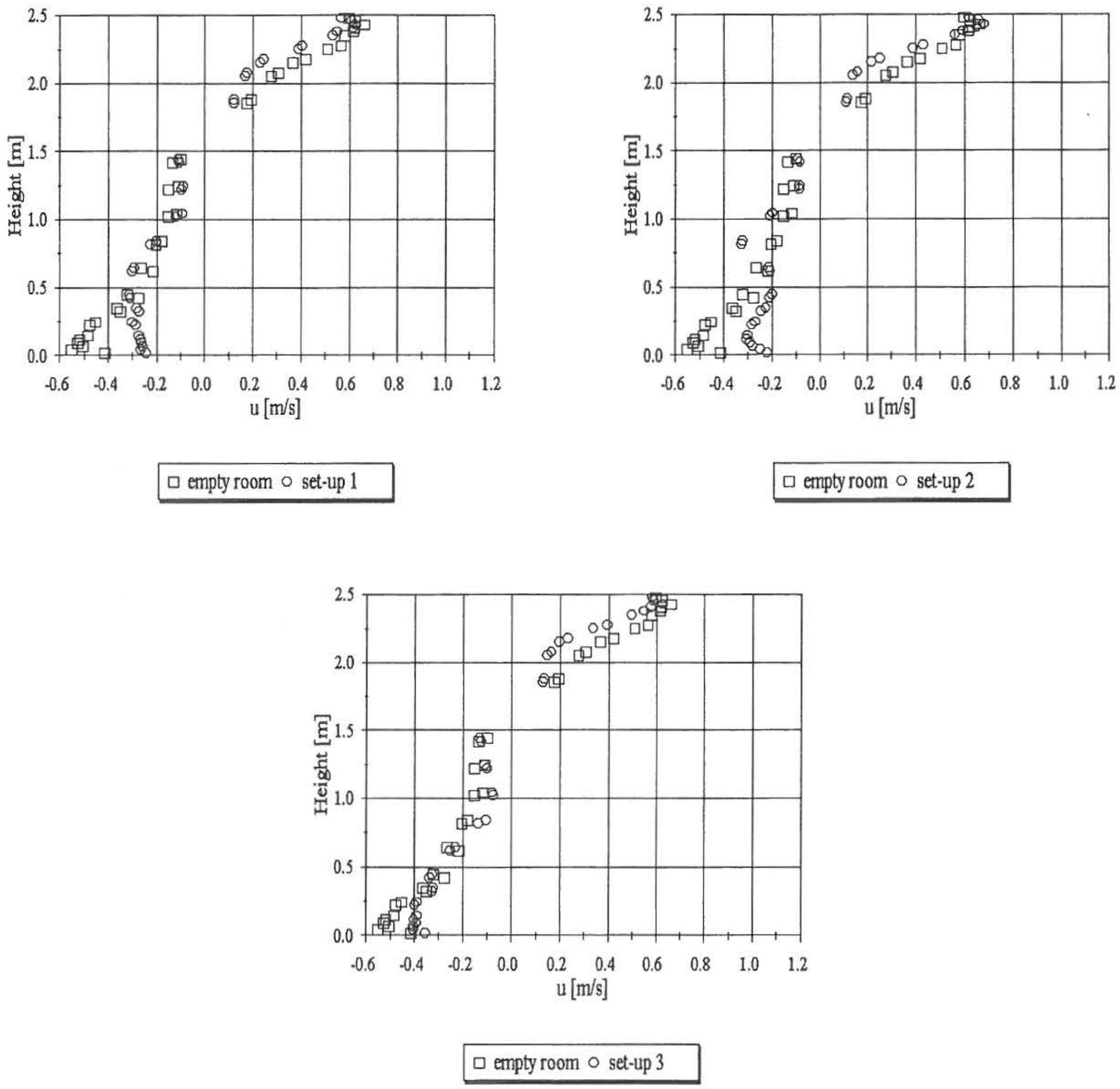
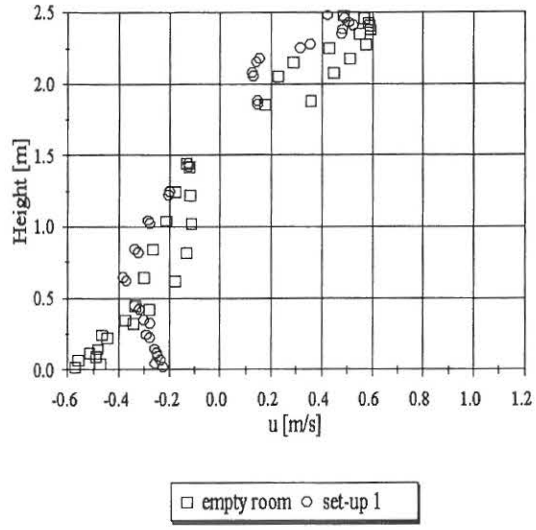


Figure 2.14 *The measured velocity profiles 3.00 m from the inlet in the empty room and in the three furnished rooms.*

At a distance of 3.00 m from the inlet the same tendency is seen as 2.00 m from the inlet (figure 2.13). The influence of the furniture grows as the distance from the inlet increases and as the distance to the furniture decreases. In the occupied zone it can be seen in set-up 2 that the air in the centre line of the room is forced over the desks at the end wall instead of continuing to the floor (see also figure 2.9). This causes the velocity at this point to be larger than in the empty room and hereby, the deformation of the velocity profile has become more clearly.



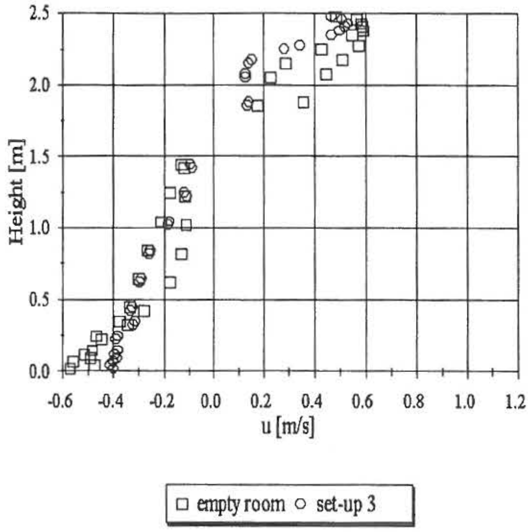


Figure 2.15 *The measured velocity profiles 4.00 m from the inlet in the empty room and in two of the furnished rooms.*

4.00 m from the inlet no velocity profile is drawn for set-up 2 because measurements are not made at this point because of the desks (see figure 2.8). The measurements in the empty room are scattered because of the problems with the unsteady jet (see section 2.1.1.2). In set-up 1 and 3 the air flow in the lower part of the room is influenced by the furniture like closer to the inlet and the deformation of the velocity profile is marked.

As found from the investigation of the velocity level and the velocity profiles, the jet under the ceiling does not seem to be influenced much by the furniture. By studying the velocity decay under the ceiling and the length scale (defined as the distance from the ceiling to half the maximum velocity of the jet at the ceiling /7/ and /30/) the influence on the jet under the ceiling is investigated further (see figure 2.16).

The length scale, δ, is determined by /30/:

$$\frac{\delta}{h} = D_p \frac{x + x_0}{h} \tag{2.1}$$

where δ : Length scale [m].
h : Height of the supply opening [m].
D_p : Growth rate.
x : Distance from the supply opening [m].
x_0 : The distance to the virtual origin of the jet [m].

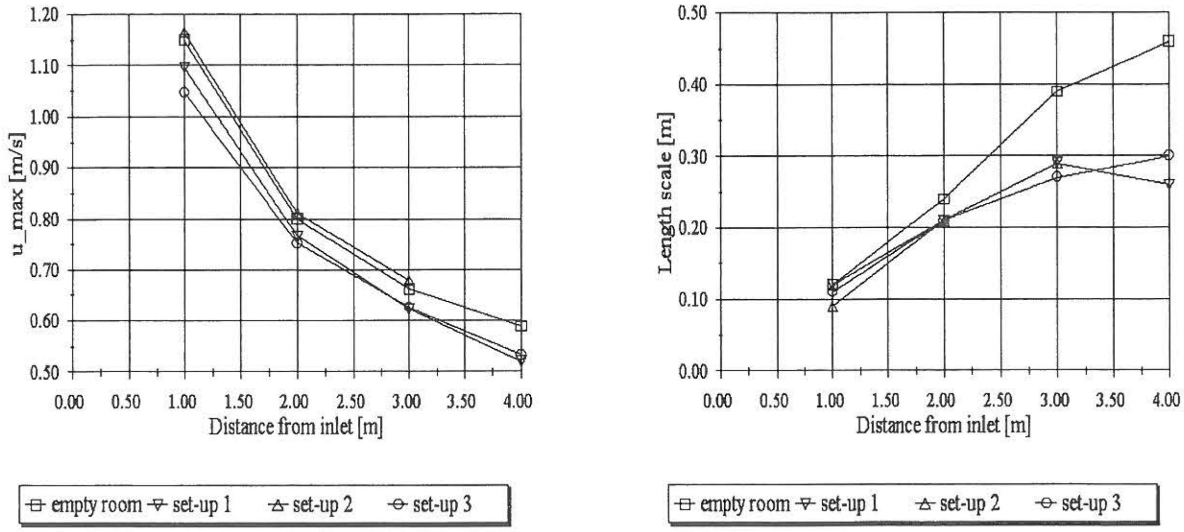


Figure 2.16 *The velocity decay under the ceiling to the left (u_{max} is the maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet.*

The figure shows that the empty room and the three set-ups with office furniture have almost the same velocity decay through the room. The length scale is higher in the empty room than in the three furnished rooms, especially 3.00 and 4.00 m from the inlet. This difference can be caused by the problems with the 2-dimensional flow at the ceiling (see section 2.1.1.2) so that the flow still not is completely 2-dimensional. It is also indicated that the development in D_p decreases with the distance from the inlet in the furnished rooms.

To see if the difference in δ is decisive, the individual constant of the diffuser, K_p, is investigated. If the value of K_p is identical in the empty room and in the three furnished rooms then the jet under the ceiling is not influenced by the furniture.

When the velocity decay is known the individual constant of the diffuser, K_p, can be found by /7/, /27/, /30/ and /36/:

$$\frac{u_{max}}{u_0} = K_p \sqrt{\frac{h}{x + x_0}} \tag{2.2}$$

where
u_{max} : Maximum velocity of the jet at the distance x from the supply opening [m/s].
u_0 : Inlet velocity [m/s].
K_p : Individual constant of the diffuser.
h : Height of the supply opening [m].
x : Distance from the supply opening [m].
x_0 : The distance to the virtual origin of the jet [m].

x_0 is found where the regression line in figure 2.16 to the right intersects with the x-axis according to equation 2.1. x_0 is 0.0 m in both the empty room and in the three furnished rooms. The individual constant of the diffuser, K_p, also identical in all the experiments and it is approximately 3.2. Therefore, it can be concluded on the basis of these experiments that typical office furniture does not influence the jet under the ceiling under isothermal conditions. Thereby, the air movements in the upper part of the room are unaffected by normal office furniture in the half of the room opposite the inlet.

The air movements in the lower part of the room are influenced by the furniture as seen from the velocity level and from the shape of the velocity profile (see figure 2.10 and figure 2.12 to 2.15). How large the influence from the furniture is on the maximum velocity in the occupied zone can be seen in table 2.1. The maximum velocity is found in the centre line of the room and to ensure that no local velocity exceeds the maximum velocity in the centre line, velocities at critical places such as on the top of the desks and in the floor area close to the desks are measured. These velocities do not exceed the velocity measured in the centre-line of the room. In general the maximum velocity, u_{rm}, is the highest measured velocity in the total occupied zone.

	empty room	set-up 1	set-up 2	set-up 3
u_{rm} [m/s]	0.557	0.383	0.343	0.410
$u_{rm}/u_{rm,0}$		0.69	0.62	0.74

Table 2.1 *The maximum velocity in the occupied zone found in the experiments, u_{rm}. The maximum velocity in the occupied zone in the three furnished rooms is compared with the one found in the empty room, $u_{rm,0}$.*

Table 2.1 shows that the maximum velocity in the occupied zone is reduced by approximately 30% in the furnished room. The reduction is larger in set-up 2 than in the other two set-ups and it is caused by the desks that are covering the centre line of the room where also the velocity measurements are made (see figure 2.8).

The experiments with the 3-dimensional slot inlet and with the two radial jets with swirl are now examined to see if the same trend in the air movements is found when a different type of inlet and geometry is used.

2.1.2 Experiments with the 3-dimensional Slot Inlet

The experiments are carried out in an insulated full-scale room with the dimensions (L×W×H) 6.00×4.00×2.80 m. The inlet is a 0.02 m wide slot across the ceiling. The slot is divided into three major parts of 1.20 m that each is divided into eight parts of 0.15 m. The distance between two of the major parts is 0.13 m and the distance from the side wall to the inlet is 0.07 m. The air is injected into the room in two opposite directions (see figure 2.17).

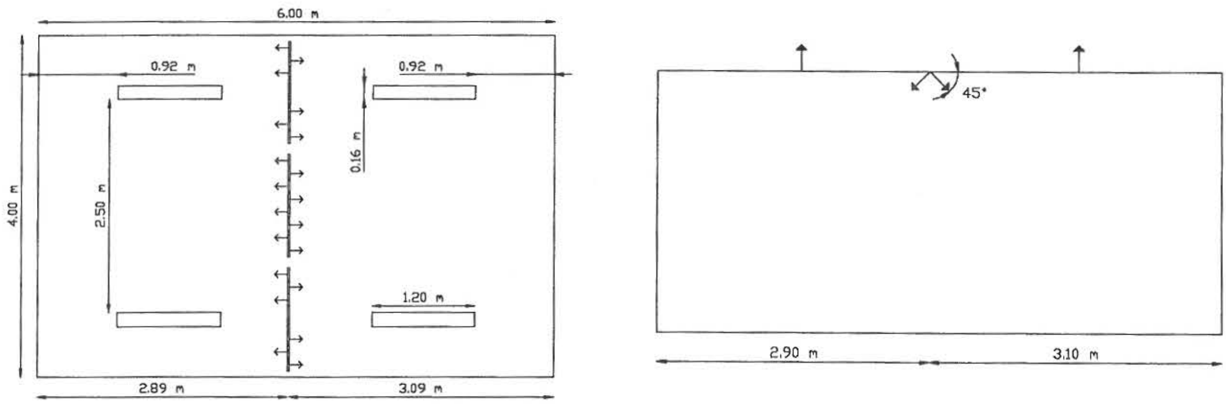


Figure 2.17 *The 3-dimensional slot inlet seen from above and from the side.*

The inlet velocity used in the experiments is 2.75 m/s for the two side parts of the inlet and 2.10 m/s for the middle part of the inlet. The difference in velocity is caused by two closed small inlet parts in each of the side inlets. The air is injected into the room in an angle of approximately 45°.

The air in the room is exhausted through four lamps. These are located symmetrically in the room and their dimensions are (L×W) 1.20×0.16 m. The lamps are built in so that the lowest part of them levels the ceiling.

2.1.2.1 Measuring Equipment
Like in the experiments with the 2-dimensional slot inlet (see section 2.1.1) mainly velocities are measured in the room. To make sure that isothermal conditions are present, the inlet and the exhaust temperature are measured. It is also made sure that the inlet velocity is constant.

The velocity measurements are made in 15 points equally distributed over the floor area where the distance between them is 1.00 m (see figure 2.18).

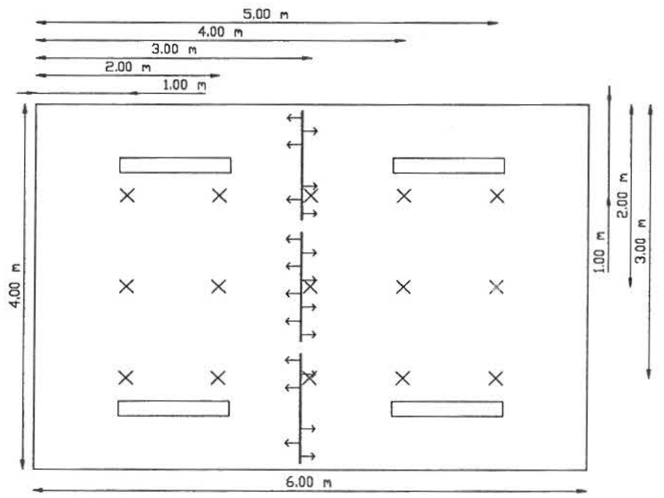


Figure 2.18 The points where velocity is measured (×).

The velocity measurements are made with two instruments: a low velocity flow analyser type 54N50 from Dantec and a low velocity flow analyser type 54N50 from Disa. Though two different trademarks are used, the principle for measuring is the same (for description see section 2.1.1.1). To each anemometer only one transducer is connected.

In the experiments the velocity is measured in 20 heights between the floor and the ceiling (see figure 2.19).

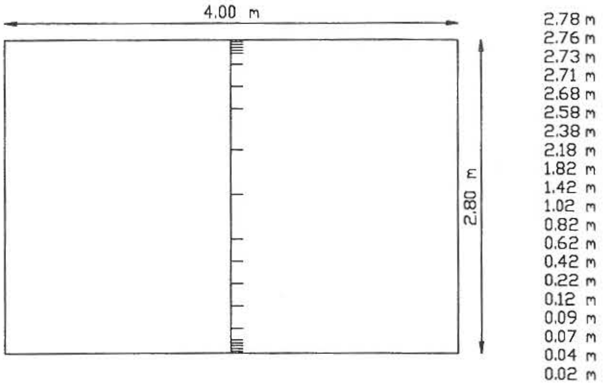


Figure 2.19 *The heights where velocity is measured.*

Like in the experiments with the 2-dimensional slot inlet the distance between the measuring points is decreased close to the floor and close to the ceiling. The measurements are made with an integration time of 200 seconds and 180 seconds for the anemometer from Dantec and Disa, respectively. This difference is determined by the instruments because there are only fixed time values possible.

2.1.2.2 The Flow in the Empty Room

The measurements made in the empty room are used as reference to the measurements made in the furnished room, like it was the case with the 2-dimensional slot inlet (see section 2.1.1).

By adding smoke to the air, the air movements in the room are visualized. In the room with the 3-dimensional slot inlet, the air moves along the ceiling to the end wall in both directions. Here the jet deflects down along the wall but only a part of the air reaches the floor. The rest of the air is deflected into the middle of the room on its way down to the floor. Figure 2.20 shows the air movements in the room.

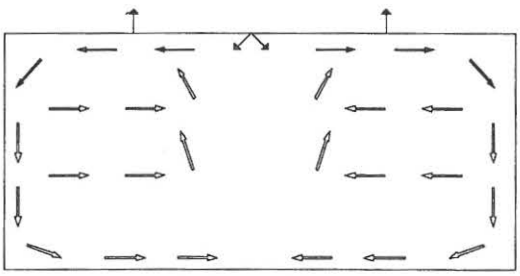


Figure 2.20 *The air movements in the empty room.*

The velocity measurements and the analyses of them are presented in connection with the results found in the furnished rooms (see section 2.1.2.5).

2.1.2.3 Experimental Set-up with Office Furniture

In the room with the 3-dimensional slot inlet only one set-up is made with office furniture. The furniture consists of two desks (LxWxH) 1.55x0.77x0.79 m, two computers (LxWxH) 0.425x0.42x0.18 m with monitors on the top (LxWxH) 0.30x0.30x0.38 m and two sitting dummies representing sitting persons. The following figure shows the measures of the dummy.

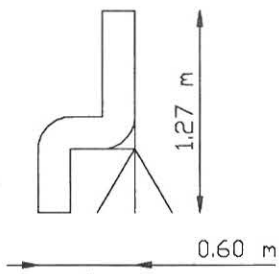


Figure 2.21 *Sketch of the sitting dummy. The chair is 0.40 m wide.*

In the set-up with office furniture a desk with a computer on the top is placed in each half of the room and a sitting dummy is placed at each desk (see figure 2.22). The dummy is located as if it is sitting at the table and therefore only 0.46 m of it is visible.

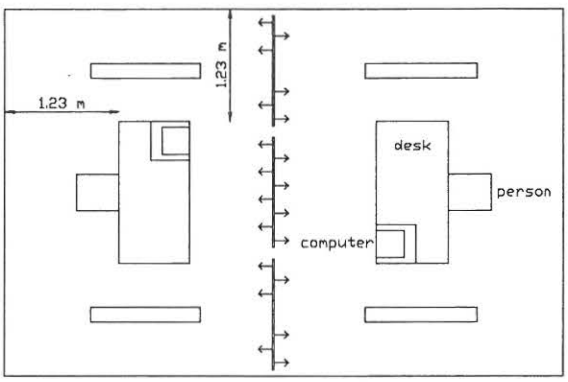


Figure 2.22 *The set-up with office furniture.*

2.1.2.4 The Flow in the Room with Office Furniture

The air movements in the furnished room are studied visually by adding smoke to the inlet air. The velocities measured in the room are presented in section 2.1.2.5 where they are compared with the measurements made in the empty room.

In the experiment with the 3-dimensional slot inlet the furniture in the room does not influence the overall air movements in room. Figure 2.23 shows the air movements in the room with furniture. For a description of the flow see section 2.1.2.2.

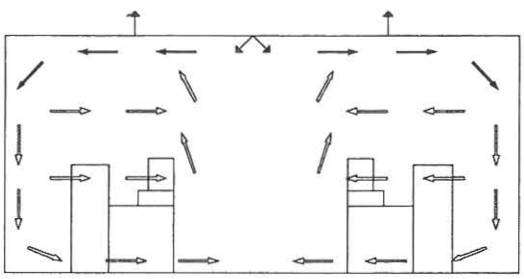
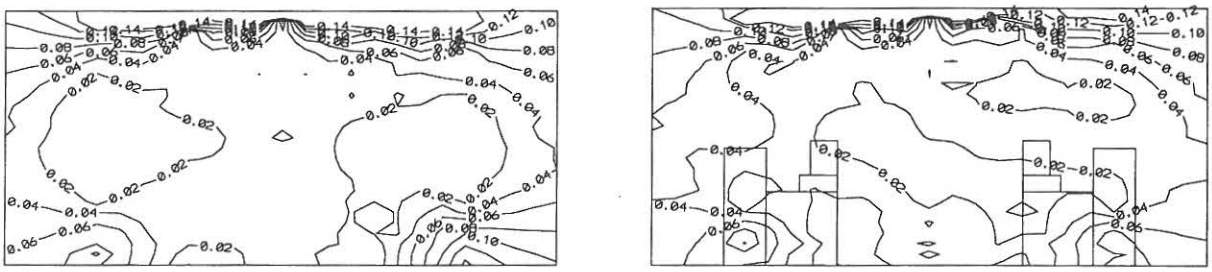


Figure 2.23 *The air movements in the furnished room.*

2.1.2.5 Differences Between the Empty and the Furnished Room

It was found in the experiments made with the 2-dimensional slot inlet and normal office furniture (see section 2.1.1.5) that the furniture does not influence the air movements under the ceiling whereas the flow in the lower part of the room is affected by the furniture. Hereby, the velocity profile is changed and the maximum velocity in the occupied zone is reduced. Similar investigations are made of the velocity measurements carried out in the room with the 3-dimensional slot inlet.

By using the average value of the measured velocity across the room (see figure 2.18) the velocity level in the room is found by interpolating with the method Kriging (see footnote 1 page 10). Like in the room with the 2-dimensional slot inlet, the wall velocity of 0.0 m/s is not used in the interpolation because the distance from the end wall to the point of measurement is to big to get a realistic representation of the results. The following figure shows the measurements made in the empty and the furnished room with the 3-dimensional slot inlet.



Empty room *Furnished room*

Figure 2.24 *The velocity level in the empty room and in the furnished room with the 3-dimensional slot inlet.*

In figure 2.24 only velocities lower or equal to 0.14 m/s are shown. By comparing the furnished room with the empty room it is seen that the velocity level at the ceiling is almost similar in the two rooms. In the middle of the room the velocities in the furnished room are slightly higher than the velocities found in the empty room. This is caused by the furniture that forces the air to move around and above it, like it was the case with the 2-dimensional slot inlet but the quantity of forced air is so small that it is not visual when smoke is added to the air. Close to the floor it is found that the velocity level in the furnished room is reduced compared with the empty room. This was also expected in the light of the experiments with the 2-dimensional slot inlet.

Hereby, the same picture of the influence from office furniture on the overall air movements in the room is found in both the room with the 2-dimensional slot inlet (see section 2.1.1.5) and in the room with the 3-dimensional slot inlet.

To investigate the influence from the furniture more closely the velocity profiles measured in the room is studied. The distance from the left end wall in figure 2.18 is used as reference and the velocities are drawn positive when the flow moves from the left end wall to the right one (see figure 2.25).

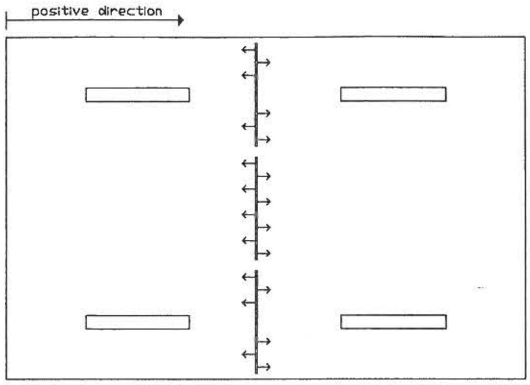
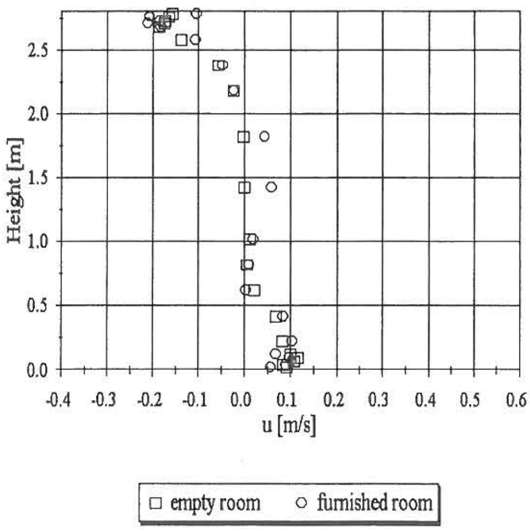
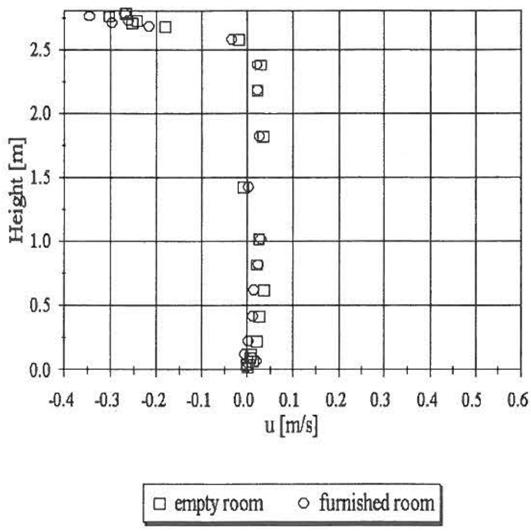


Figure 2.25 Definition of the positive direction for the velocities.

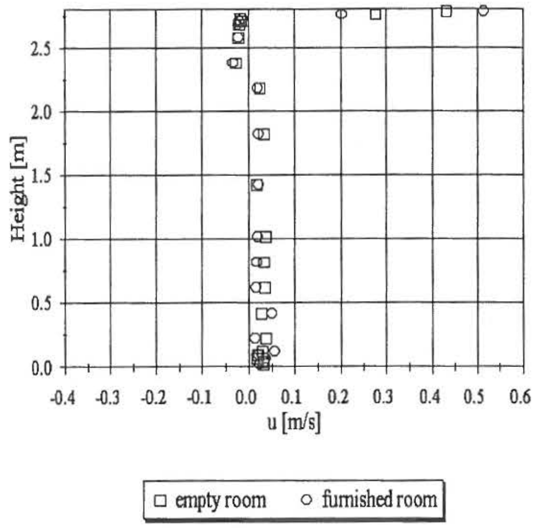
By drawing the velocity profiles the average value of the velocity across the room is used like it was the case by drawing the velocity level in the room.



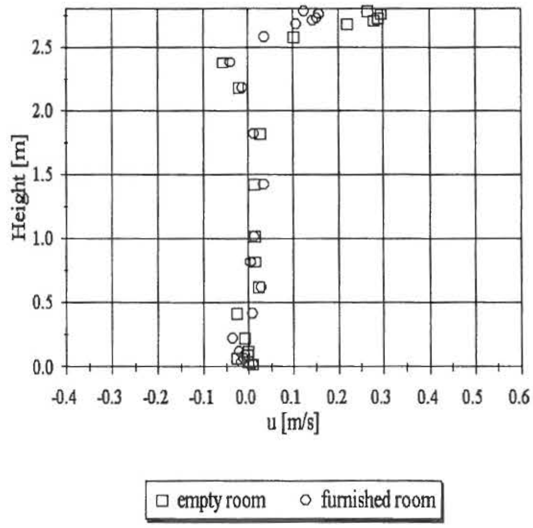
1.00 m from the end wall



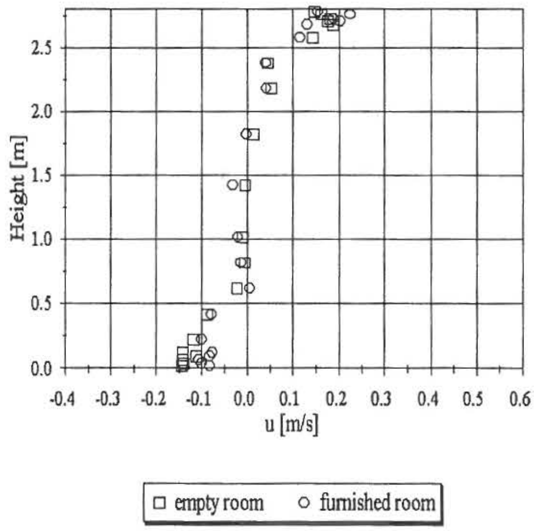
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



5.00 m from the end wall

Figure 2.26 *The average velocity profiles measured 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with the 3-dimensional slot inlet. The slot inlet is located 2.90 m from the left end wall.*

In the room with the 3-dimensional slot inlet it is found by studying the velocity profiles through the room (figure 2.26) that under the ceiling does the furniture only influence the velocities slightly whereas in the lower part of the room, the velocity profile in the furnished room is deformed. This deformation is most clearly farthest from the inlet and it results in a small enhancement in the velocities in the middle of the room and in a reduction of the velocity close to the floor. This was also found by studying the velocity level (see figure 2.24).

Hereby, it is found by studying the velocity profiles that the jet under the ceiling is not influenced by the furniture but the velocities in the lower part of the furnished room are decreased by which the velocity profile is deformed. This was also found in the experiments with the 2-dimensional slot inlet (see section 2.1.1.5).

To study more closely if the jet under the ceiling is unaffected by the furniture, the velocity decay under the ceiling and the length scale, δ, are investigated. Figure 2.27 shows the two parameters in the room with the 3-dimensional slot inlet and the values are measured on both sides of the inlet. The maximum velocity at the ceiling in connection with the velocity decay is shown as the absolute value and δ is defined as the distance from the ceiling to $u_{max}/2$ /7/ and /30/ (see also equation (2.1) page 15).

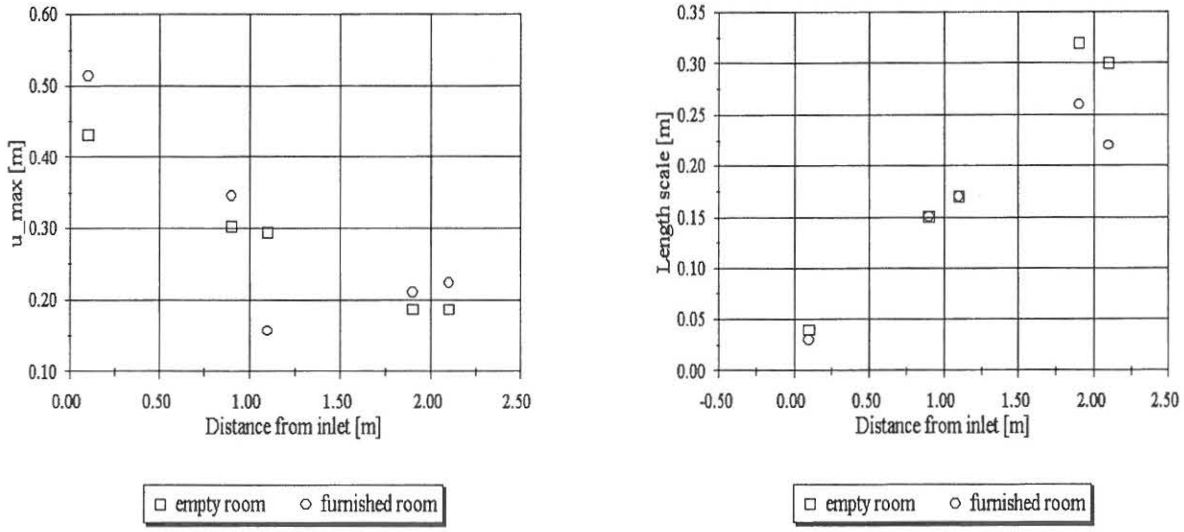


Figure 2.27 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The 3-dimensional slot inlet is located 2.90 m from the left end wall.*

In figure 2.27 it is seen that the maximum velocity at the ceiling in the furnished room is higher than the one found in the empty room except 1.10 m from the inlet. This difference can be caused by an inaccuracy in the measurements of u_{max} so that the point of the maximum velocity is not measured but a measurement is made close to the location of the maximum velocity. This is a result of the distance between the measuring points. That the measurements are acceptable can be seen from the length scale that is almost identical in the two rooms. Only close to the end walls in the room (1.90 and 2.10 m from the inlet) a difference occurs. This behaviour was also found in the room with the 2-dimensional slot inlet. The jet under the ceiling is probably unaffected by the furniture and to see if the jet actually is uninfluenced by the furniture, the individual constant of the diffuser is studied in the empty and in the furnished room.

The individual constant of the diffuser, K_p, is found from equation (2.2) (see section 2.1.1.5 page 16) but first the distance to the virtual origin of the jet, x_0, has to be found. The distance to the virtual origin of the jet, x_0, is found by investigating the length scale and in both the empty and the furnished room. x_0 is found to 0.35 m in both rooms. The individual constant of the diffuser, K_p, is approximately 1.3 in both the empty and the furnished room.

Because the distance to the virtual origin and the individual constant of the diffuser are identical in the empty and the furnished room, the flow in the upper part of the room is concluded not to be influenced by the presence of furniture in the room with the 3-dimensional slot inlet.

It was found by studying the velocity level in the room (figure 2.24) and the velocity profiles (figure 2.26) that the air movements in the lower part of the room are influenced by the furniture.

The magnitude of this disturbance is found by investigating the maximum velocity in the occupied zone.

	empty room	furnished room
u_{rm} [m/s]	0.142	0.106
$u_{rm}/u_{rm,0}$		0.75

Table 2.2 *The maximum velocity in the occupied zone found in the empty and the furnished room. The velocity in the furnished room, u_{rm}, is compared with the one found in the empty room, $u_{rm,0}$.*

In table 2.2 it is seen that the maximum velocity in the occupied is reduced 25% when furniture is present in the room. The reduction is a little less than the reduction found in the three set-ups with the 2-dimensional slot inlet (see table 2.1 in section 2.1.1.5 page 17). This difference can be caused by the location of the measuring points that were only in the centre line of the room with the 2-dimensional slot inlet, whereas an average value across the room is used in this case.

To see if the same results regarding the jet under the ceiling and the maximum velocity in the occupied zone can be found with another type of inlet, experiments with two radial jets with swirl are made.

2.1.3 Experiments with the Two Radial Jets with Swirl

The experiments are carried out in an insulated full-scale room with the dimensions (L×W×H) 6.00×4.00×2.80 m. This room is also the same as the one used in the experiments with the 3-dimensional slot inlet. The inlet consists of two radial jets with swirl and they are located with one in the middle of each half of the room. The inlet is circular with a diameter of 0.18 m and it is divided into eight parts (see figure 2.28). The inlet creates an anticlockwise rotating jet at the beginning and this jet is then transformed into an almost radial jet along the ceiling and therefore, it is here called a radial jet with swirl.

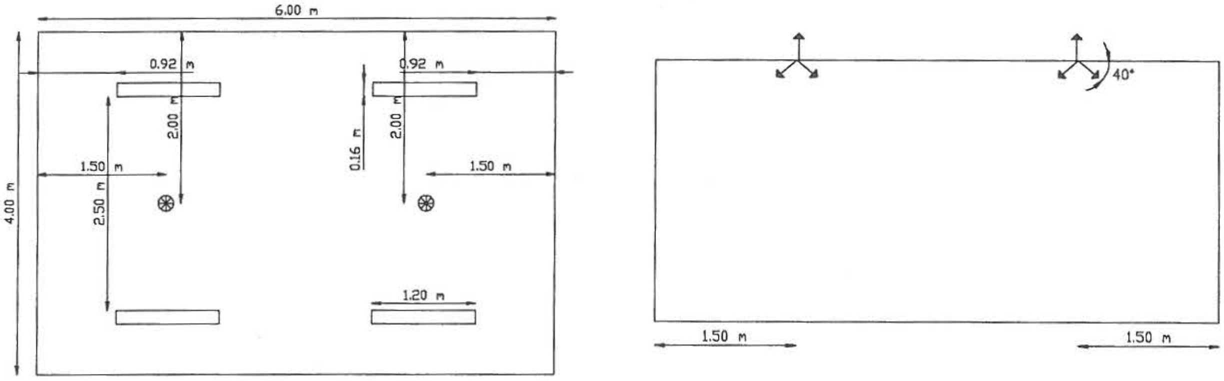


Figure 2.28 *The two radial jets with swirl seen from above and from the side.*

In all the experiments an inlet velocity of 2.77 m/s is used and the air is injected into the room in an angle of approximately 40°.

The air in the room is exhausted through four lamps. These are located symmetrically in the room and their dimensions are (L×W) 1.20×0.16 m. The lamps are built in so that the lowest part of them levels the ceiling.

2.1.3.1 Measuring Equipment

Like in the experiments with both the 2-dimensional and the 3-dimensional slot inlet (see section 2.1.1 and 2.1.2) mainly velocities are measured in the room. To make sure that isothermal conditions are present, the inlet and the exhaust temperature are measured. It is also made sure that the inlet velocity is constant.

The velocity measurements are made in 15 points equally distributed over the floor area where the distance between them is 1.00 m (see figure 2.29).

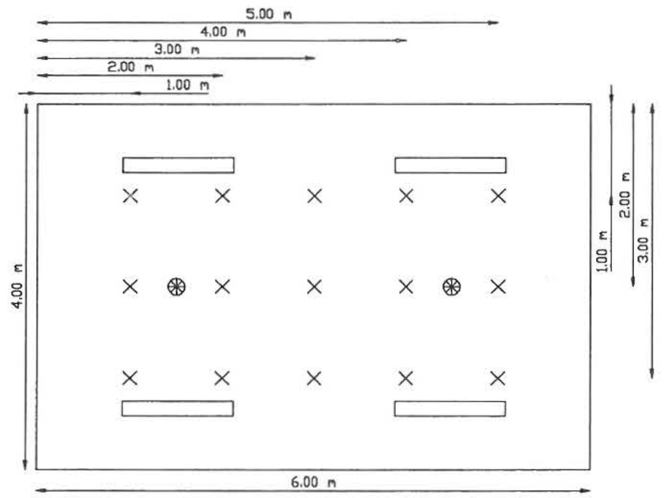


Figure 2.29 The points where velocity is measured (×).

The velocity measurements are made with the same two instruments as was used in the experiment in the room with the 3-dimensional slot inlet (see section 2.1.2.1 page 18).

In the experiments the velocity is measured in 20 heights between the floor and the ceiling (see figure 2.30).

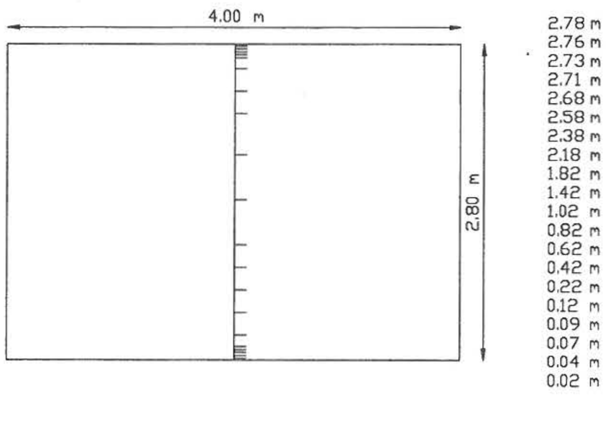


Figure 2.30 The heights where velocity is measured.

Like in the experiments with both the 2-dimensional and the 3-dimensional slot inlet the distance between the measuring points is decreased close to the floor and close to the ceiling. The measurements are made with an integration time of 200 seconds and 180 seconds for the anemometer from Dantec and Disa, respectively. This difference is determined by the instruments because there are only fixed time values possible.

2.1.3.2 The Flow in the Empty Room

The measurements made in the empty room are used as reference to the measurements made in the furnished room, like it was the case with both the 2-dimensional and the 3-dimensional slot inlet (see section 2.1.1 and 2.1.2).

In the room with the two radial jets with swirl, the inlet jets meet in the middle of the room where the air moves down towards the floor. At the sides of the room, the air moves along the ceiling to the end wall where it is deflected downwards but only a very little part of the air reaches the floor. Instead the air moves to the middle of the room (see figure 2.31).

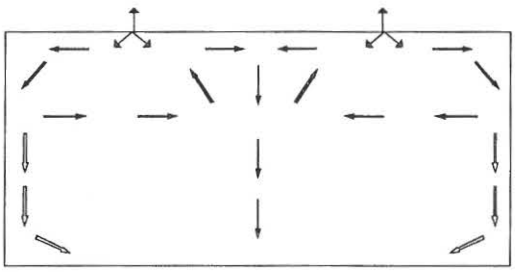


Figure 2.31 The air movements in the empty room.

The velocity measurements and the analyses of them are presented in connection with the results found in the furnished rooms (see section 2.1.3.5).

2.1.3.3 Experimental Set-up with Office Furniture

In the room with two radial jets with swirl the same set-up with office furniture is used as in the room with the 3-dimensional slot inlet. Section 2.1.2.3 describes the furniture and the set-up and the latter is also shown in figure 2.32.

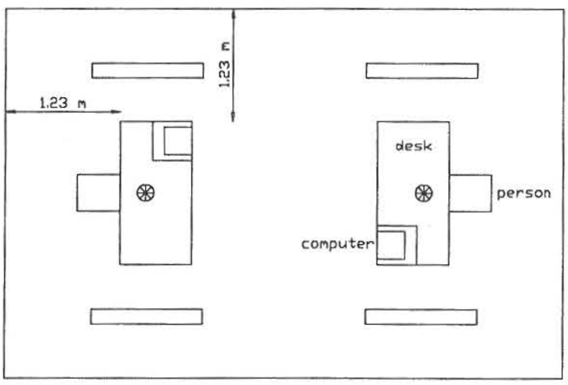


Figure 2.32 The set-up with office furniture.

2.1.3.4 The Flow in the Room with Office Furniture

The air movements in the furnished room are studied visually by adding smoke to the inlet air. The velocities found in the room are presented in section 2.1.3.5 where they are compared with the measurements made in the empty room.

In the experiment with the two radial jets with swirl the furniture in the room does not influence the overall air movements in room. Figure 2.33 shows the air movements in the room with furniture. For a description of the flow see section 2.1.3.2.

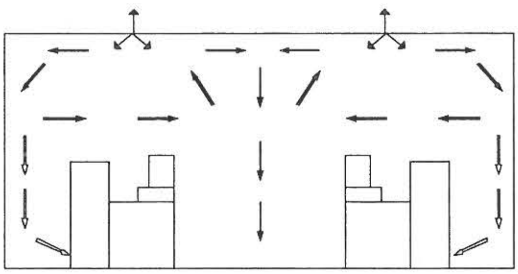
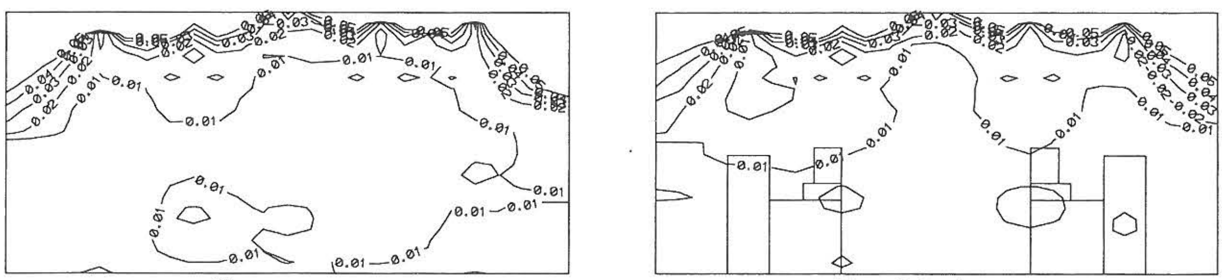


Figure 2.33 *The air movements in the furnished room.*

2.1.3.5 Differences Between the Empty and the Furnished Room

It was found in the experiments made with normal office furniture in the room with the 2-dimensional slot inlet and in the room with the 3-dimensional slot inlet (see section 2.1.1.5 and 2.1.2.5) that normal office furniture does not influence the air movements under the ceiling whereas the flow in the lower part of the room is affected by the furniture. Hereby, the velocity profile is changed and the maximum velocity in the occupied zone is reduced. Similar investigations are made of the velocity measurements carried out in the room with the two radial jets with swirl.

By using the average value of the measured velocity across the room (see figure 2.29) the velocity level in the room is found by interpolating with the method Kriging (see footnote 1 page 10). Like in the rooms with the 2-dimensional and the 3-dimensional slot inlet, the wall velocity of 0.0 m/s is not used in the interpolation because the distance from the end wall to the point of measurement is to big to get a realistic representation of the results. The following figure shows the measurements in the empty and the furnished room with two radial jets with swirl.



Empty room *Furnished room*

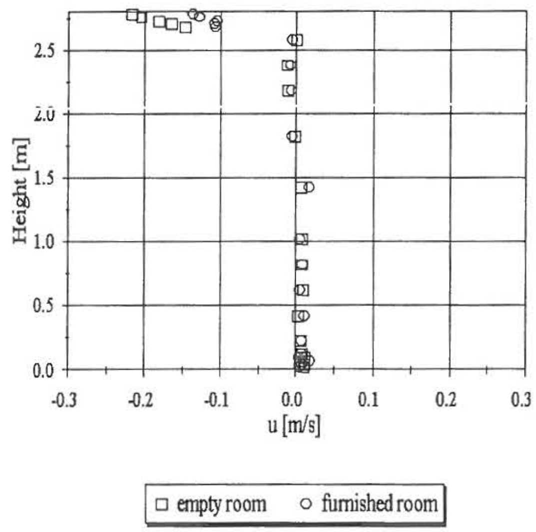
Figure 2.34 *The velocity level in the empty room and in the furnished room with the two radial jets with swirl.*

In figure 2.34 only velocities equal to or lower than 0.05 m/s are shown. In the ceiling area no particular difference occurs between the empty and the furnished room. In the lower part of the room, the air is almost stagnant but the velocity level is slightly increased in the middle of the furnished room compared with the empty room like it was the case with both the 2-dimensional and the 3-dimensional slot inlet. In the floor area the velocity level is slightly reduced in the furnished room which also was expected from the other experiments. As it can be seen from the figure, the velocity level in the room is very low. This is because it is chosen to use a realistic air exchange rate of 2.9 h^{-1} which also was used in the room with the 3-dimensional slot inlet.

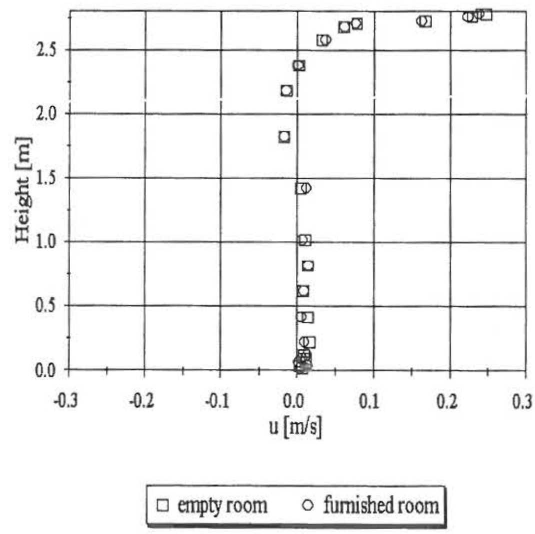
Hereby, the same overall picture of the influence from office furniture on the overall air movements in the room is found with all three inlet types. The influence on the flow in the room is independent on the used set-up (four different have been tried out) and the inlet type (three different have been tested).

To investigate the influence from the furniture more closely in the room with the two radial jets with swirl, the velocity profiles measured in the room are studied. The distance from the left end wall in figure 2.29 is used as reference and the velocities are drawn positive when the flow moves from the left end wall to the right one (see figure 2.25 page 22).

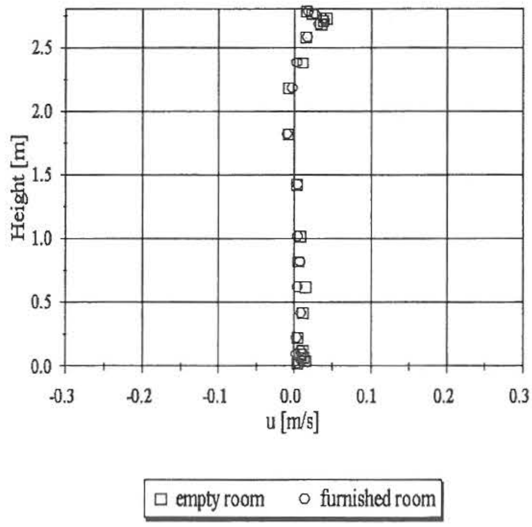
By drawing the velocity profiles the average value of the velocity across the room is used like it was the case by drawing the velocity level in the room.



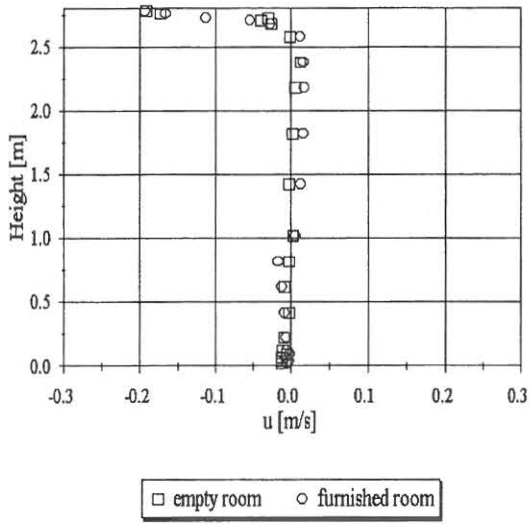
1.00 m from the end wall



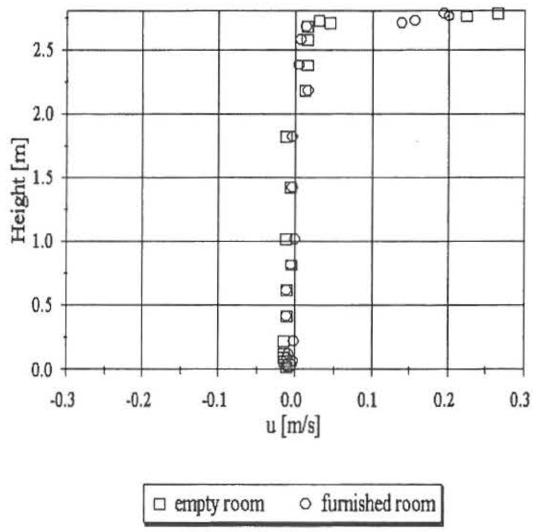
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



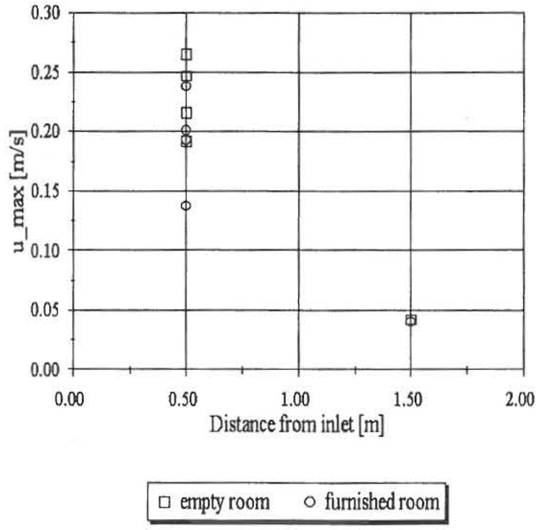
5.00 m from the end wall

Figure 2.35 *The average velocity profiles measured 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with two radial jets with swirl. The diffusers are located 1.50 and 4.50 m from the left end wall.*

In the room with two radial jets with swirl as inlet system, the velocity profiles through the room (figure 2.35) show almost no influence from the furniture on the velocity in the room. Only close to the floor a small reduction of the velocity in the furnished room can be seen. The velocity profile 3.00 m from the left end wall indicates a velocity of almost 0.0 m/s. This is caused by the downward direction of the velocity (see figure 2.31 and 2.33) combined with the self convection of the anemometer.

Hereby, it was found by studying the velocity profiles in all the situations tested in the experiments with the three inlet types, that the jet under the ceiling is not influenced by the furniture but the velocities in the lower part of the furnished room are decreased by which the velocity profile is deformed.

To study more closely if the jet under the ceiling is unaffected by the furniture in the room with the two radial jets with swirl, the velocity decay under the ceiling and the length scale, δ, are investigated (see figure 2.36). In the figure values from both sides of the inlets are included. The maximum velocity at the ceiling in connection with the velocity decay is shown as the absolute value and δ is defined as the distance from the ceiling to $u_{max}/2$ /7/ and /30/ (see also equation (2.1) page 15).



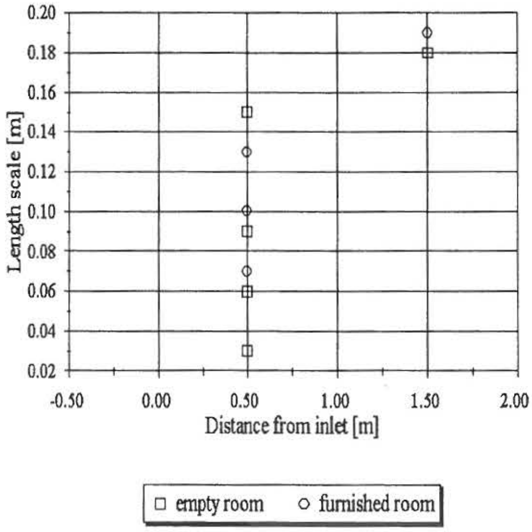


Figure 2.36 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The two radial jets with swirl are located 1.50 and 4.50 m from the left end wall.*

It can be seen in figure 2.36 that the maximum velocity at the ceiling and the length scale have some scattering. This probably arises from the difference in the two measuring points 0.5 m from one inlet - one is located towards the middle of the room and the other is located towards the end wall. Hereby, the two measuring points are affected differently because of the wall. The scattering is also found because the average value across the room is used instead of the real distance from the inlet to the individual measuring points. It is from the two graphs in figure 2.36 difficult to evaluate if the jet under the ceiling is affected by the furniture. The individual constant of the diffuser is studied together with the distance to the virtual origin to be able to find out if a difference between the two rooms is present.

The individual constant of the diffuser is in this case determined by /36/:

$$\frac{u_{max}}{u_o} = K_{rs}\frac{\sqrt{a_0}}{x+x_0} \tag{2.3}$$

where u_{max} : Maximum velocity of the jet at the distance x from the supply opening [m/s].
u_0 : Inlet velocity [m/s].
K_{rs} : Individual constant of the diffuser.
a_0 : Area of the supply opening [m²].
x : Distance from the supply opening [m].
x_0 : The distance to the virtual origin of the jet [m].

By studying the length scale, the distance to the virtual origin is 0.35 m in both the empty and the furnished room. The individual constant of the diffuser is also identical in both situations and it is found to approximately 0.4. The low K_{rs} value is very typical for flow with a swirl /4/ and for axial jets with swirl /31/. Because x_0 and K_{rs} are identical in the empty and the furnished room, the flow in the upper part of the room is concluded not to be influenced by the presence of furniture in the room with the two radial jets with swirl.

Hereby, it can also be concluded on the basis of these experiments that the flow in the upper part of the room is not influenced by the furniture. This is the same as was found in all the other experiments so presumably does the presence of furniture not disturb the flow near to the ceiling when air is injected into the upper part of the room. In the simulations with the 2-dimensional slot inlet is investigated if this behaviour is independent of the location and size of the furniture.

It was found by studying the velocity level in the room with two radial jets with swirl (figure 2.34) and the velocity profiles (figure 2.35) that the air movements in the lower part of the room are influenced by the furniture. The magnitude of this disturbance is found by investigating the maximum velocity in the occupied zone.

	empty room	furnished room
u_{rm} [m/s]	0.015	0.011
$u_{rm}/u_{rm,0}$		0.73

Table 2.3 *The maximum velocity in the occupied zone found in the empty and the furnished room. The velocity in the furnished room, u_{rm}, is compared with the one found in the empty room, $u_{rm,0}$.*

In table 2.3 can be seen that the maximum velocity in the occupied is reduced with 27% when furniture is in the room. The reduction is approximately the same as was found in the rooms with the 2-dimensional and the 3-dimensional slot inlet (see table 2.1 in section 2.1.1.5 page 17 and table 2.2 in section 2.1.2.5 page 25). To investigate if the maximum velocity in the occupied zone is always reduced in a furnished room, simulations with further set-ups are made in the room with the 2-dimensional slot inlet.

The next section describes the simulations made of the experimental set-ups with normal office furniture carried out with the three types of inlets.

2.2 CFD Simulations

The isothermal CFD simulations are mainly used to make a simulation model of the experimental conditions. Further simulations are made where the set-up in the room with the 2-dimensional slot inlet is changed. This is done to find out how different sizes and locations of the furniture influence the air flow in the room.

To make the same situation as was measured in the experiments with office furniture the empty rooms are simulated at first. When the flows are matching in the empty rooms, the experiments made with office furniture are simulated. The furniture can here be inserted more or less detailed and in the investigations made in this thesis a very coarse modelling is chosen where rectangular volume resistances represent the furniture. These volume resistances generate a pressure drop and the degree of braking the air must be adjusted to the disturbances the physical furniture makes.

The simulations are made with the CFD code Flovent from Flomerics. The program uses the control volume method and in all the simulations the k-ε turbulence model is used and the roughness of the walls is set to 0 mm.

To make satisfying simulations of the experiments both 2- and 3-dimensional simulations are used. Where it is possible 2-dimensional simulations are made because it is time saving. It is normally the elaboration of the inlet that is determined. This means that only the 2-dimensional slot inlet is simulated 2-dimensionally whereas both the 3-dimensional slot inlet and the two radial jets with swirl are simulated 3-dimensionally.

As mentioned earlier a volume resistance is used instead of inserting the furniture in details. In the 2-dimensional simulations, the size of the volume resistance is set to be the total width of the room and it has the same length as the physical furniture. In the 3-dimensional simulations, the volume resistance has the actual size of the physical furniture. Hereby, in both the 2-dimensional and the 3-dimensional simulations, the volume resistances are located at the same place as the physical furniture. If more groups of furniture are present in the room, the same number of volume resistances is present.

The volume resistance is a porous medium where the air can pass through (see figure 2.37) but the air is braked because the volume resistance generates a pressure drop.

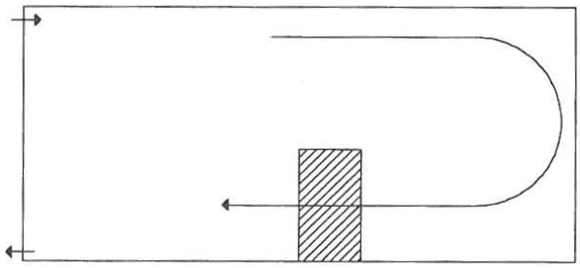


Figure 2.37 The air can pass through the volume resistance.

The pressure drop generated by the volume resistance is determined by /14/:

$$\frac{\partial p}{\partial x} = \frac{f}{2} \rho u^2 \tag{2.4}$$

where $\partial p/\partial x$: Pressure drop per m [Pa/m].
f : Loss coefficient [m^{-1}].
ρ : Air density; 1.19 kg/m^3.
u : Velocity [m/s].

The pressure drop generated by the volume resistance is handled as an additional sink in the Navier-Stokes equations. The following equation shows how it is handled in the x-direction /14/:

$$\frac{\partial}{\partial t}(\rho u)+\frac{\partial}{\partial x}(\rho uu)+\frac{\partial}{\partial y}(\rho vu)+\frac{\partial}{\partial z}(\rho wu)-\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial u}{\partial y}\right)-\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial u}{\partial z}\right)=-\left(\frac{\partial p}{\partial x}-\frac{f}{2}\rho u^2\right) \tag{2.5}$$

where u, v, w : Velocity in the x-, y- and z-direction [m/s].
μ_{eff} : Effective viscosity (laminar plus turbulent) [kg/ms].

The loss coefficient, f, in equation 2.4 must be determined so that the air flow and the velocity distribution are similar in the experimental and the simulated room with office furniture. Where more groups of furniture/volume resistances are present, the same loss coefficient is used in all the volumes. An identical loss coefficient is used so that a value representative for office furniture can be found. This value is then used in the further simulations in the room with the 2-dimensional slot inlet.

2.2.1 Simulations with the 2-dimensional Slot Inlet

The simulations of this inlet are 2-dimensional and they are divided into three major parts. At first the air movements in the simulated empty room must be identical to the air movements in the experimental empty room. Afterwards the three experiments with office furniture are simulated and a common loss coefficient in the three cases is found. Finally, additional simulations are made with other sizes and locations of the volume resistance where the loss coefficient is identical with the one found from the three experiments with office furniture. The length of the room is also varied. These additional simulations are made to investigate the conclusions found in the experiments further (see section 2.1.1.5, 2.1.2.5 and 2.1.3.5). They are also used to determine how the velocities in the room depend on the size and the location of the furniture.

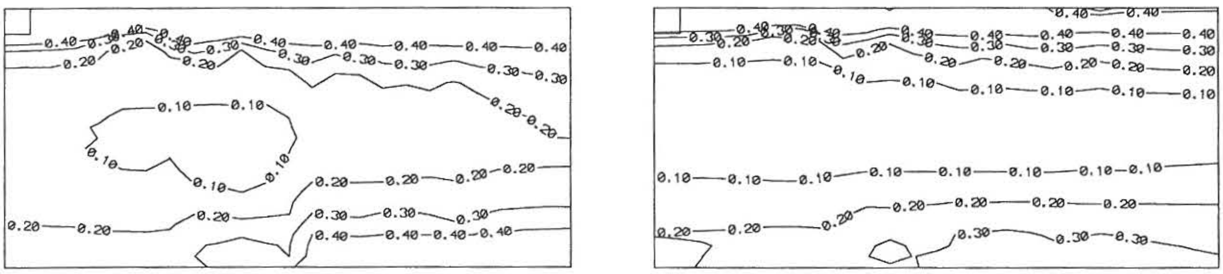
In all the simulations the inlet velocity is identical with the one used in the experiments (3.47 m/s). Because the simulations are 2-dimensional the physical exhaust that consists of two holes (see figure 2.1 page 5) is transformed into a 0.0068 m high slot with the width of the room. With this, the simulated exhaust has the same area as the physical exhaust and furthermore, the simulated exhaust is located so that its centre is in the same height above the floor as the centre of the physical holes.

2.2.1.1 The Empty Room

The flow in the simulated empty room must be similar to the flow in the experimental room and several investigations are made to evaluate the simulation. If the simulation does not agree with the experiment, some changes have to be made in the simulation model in, e.g. the construction of the inlet jet or in the grid distribution. To evaluate the simulation, the following values are compared in the experimental and the simulated empty room: the velocity level, the shape of the velocity profile, the velocity decay at the ceiling, the length scale and the maximum velocity in the occupied zone.

In the investigations of the simulated room, the values of the velocities are extracted at the same distances from the inlet as the velocity measurements are made in the experimental room (1.00, 2.00, 3.00 and 4.00 m from the inlet (see also figure 2.3 page 6)). The figures of the empty experimental room used in the comparison are also to be found in section 2.1.1 but they are repeated here for the sake of convenience.

In the simulation, the inlet is modelled as the physical inlet and this gives satisfying results as the following investigations will show. First, the velocity level in the experimental and the simulated empty room is compared (see figure 2.38).

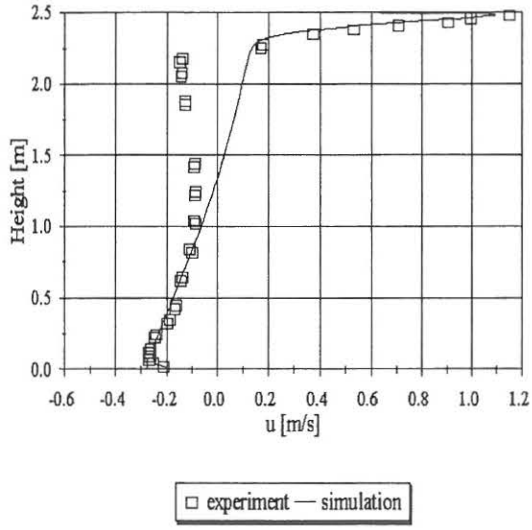


The experimental empty room *The simulated empty room*

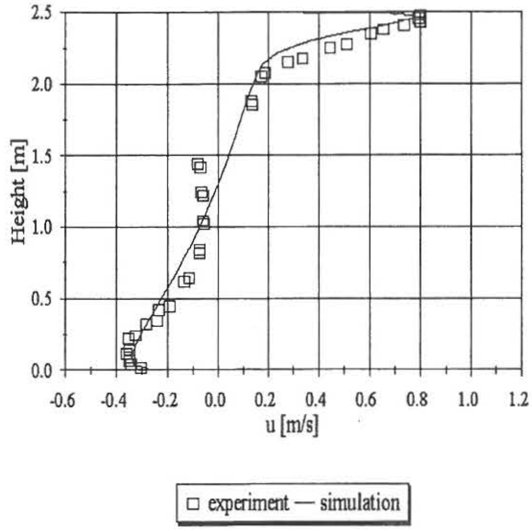
Figure 2.38 The velocity level in the experimental and simulated empty room.

In both the experimental and the simulated empty room only velocities lower or equal to 0.40 m/s are shown. It is seen in figure 2.38 that the velocity level in the simulated empty room is similar to the measured velocity level in the experimental room. The only deviation between the two rooms is the velocity level at the floor that is higher in the experimental room than in the simulated room. This deviation is studied more closely by comparing the velocity profiles through the room, the velocity decay at the ceiling, the length scale and the individual constant of the diffuser. In the evaluation of the simulation, it is more important that the velocity decay at the ceiling is similar with in the two rooms than that the flow in the rest of the room agrees. This is done because close to the ceiling the jet is not influenced by the deflection of the end wall. Furthermore, the flow in the lower part of the experimental room will be influenced by the side walls so that the flow is not completely 2-dimensional.

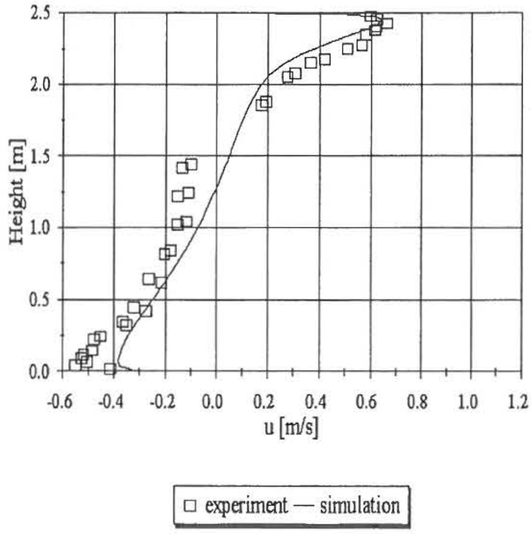
The velocity profiles 1.00, 2.00, 3.00 and 4.00 m from the inlet in the experimental and the simulated room are compared in figure 2.39. The positive direction of the velocities is defined in figure 2.11 page 11.



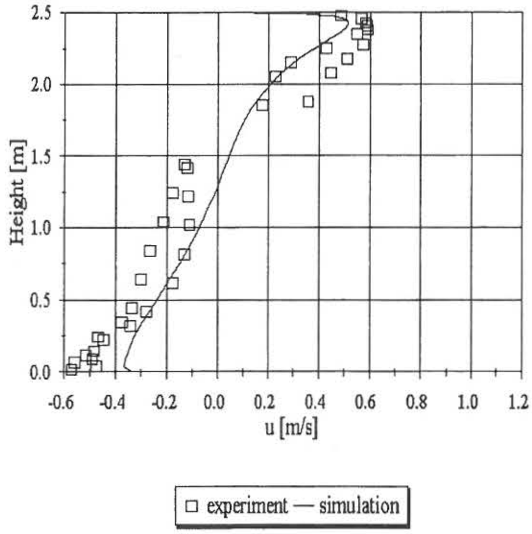
1.00 m from the inlet



2.00 m from the inlet



3.00 m from the inlet

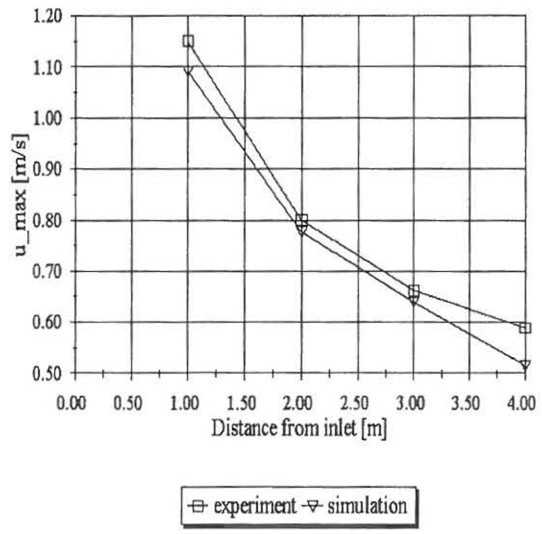


4.00 m from the inlet

Figure 2.39 *The velocity profiles found 1.00, 2.00, 3.00 and 4.00 m from the inlet in the experimental empty room and in the simulated empty room with the 2-dimensional slot inlet.*

By studying the velocity profiles in figure 2.39 it is seen that the simulated profiles are almost identical to the measured profiles in the upper part of the room. The shape of the velocity profile is also similar but the maximum velocity at the floor is lower 3.00 and 4.00 m from the inlet in the simulated room than in the experimental room. This difference can be caused by 3-dimensional effects that are present in the experimental empty room whereas the simulation is completely 2-dimensional. The reason could also be the problems with creating a completely 2-dimensional jet at the ceiling in the experiments (see section 2.1.1.2) so that the flow in the end of the room opposite the inlet is affected by this unsteady wall jet. As mentioned before, the jet at the ceiling has higher priority than the flow in the rest of the room. Therefore, the jet under the ceiling is examined more closely by studying the velocity decay, the length scale, the distance to the virtual origin of the jet and the individual constant of the diffuser.

The velocity decay at the ceiling and the length scale in the experimental and the simulated empty room are compared in figure 2.40.



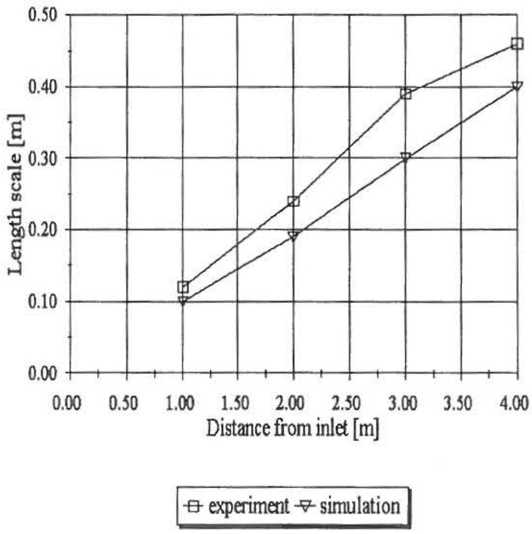


Figure 2.40 *The velocity decay under the ceiling to the left (u_{max} is the maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet.*

The velocity decay at the ceiling is similar in the experimental empty room and the simulated empty room whereas the length scale is different in the two rooms where it is highest in the experimental room. The same tendency was found in the comparison of the empty room with the three furnished rooms (see figure 2.16 page 16) so this difference is not necessarily critical. It probably comes from the problems with the unsteady experimental jet (see section 2.1.1.2). If the distance to the virtual origin and the individual constant of the diffuser are identical in the experimental and the simulated room, the simulation of the empty room is satisfying.

The distance to the virtual origin, x_0, is found where the regression line in figure 2.40 to the right intersects with the x-axis. In the simulated empty room, x_0 is found to 0.0 m which is the same value as was found in the experimental empty room. The individual constant of the diffuser, K_p, is found from equation (2.2) page 16 and K_p is approximately 3.2 in both the simulation of the empty room and in the experimental empty room.

By studying the velocity level and the velocity profiles in the experimental empty room and in the simulated empty room it was indicated that the velocity in the floor area is not identical in the two rooms. The maximum velocity in the occupied zone, $u_{rm,0}$, of the experimental room is found to 0.557 m/s whereas it is found to 0.381 m/s in the simulated room. This difference can be caused by the fact that in the experiments the flow is not completely 2-dimensional because 3-dimensional effects occur in the physical room.

It can be concluded from the investigations made in this section that the simulation of the empty room agrees satisfyingly with the experiment. This construction of the simulated room is used in all the further simulations with the 2-dimensional slot inlet.

2.2.1.2 The Three Rooms with Office Furniture

To simulate the three experiments made with office furniture, the adjusted simulated empty room is used together with volume resistances. The size and the number of the volume resistances are as mentioned earlier dependant on the physical set-up. The volume resistances have the same width as the room and their lengths are equal to the length of the furniture. This means that only two simulations are necessary to cover the three experiments made with office furniture because in set-up 2 and 3 the same lengths of furniture are present (see figure 2.8 page 9). Figure 2.41 shows the location and size of the volume resistances in the simulations of the experimental set-ups 1 to 3 with office furniture. The grid distribution is (L×H) 69×52 cells where the grid distance is smaller close to the walls, the inlet and the volume resistances than in the middle of the room.

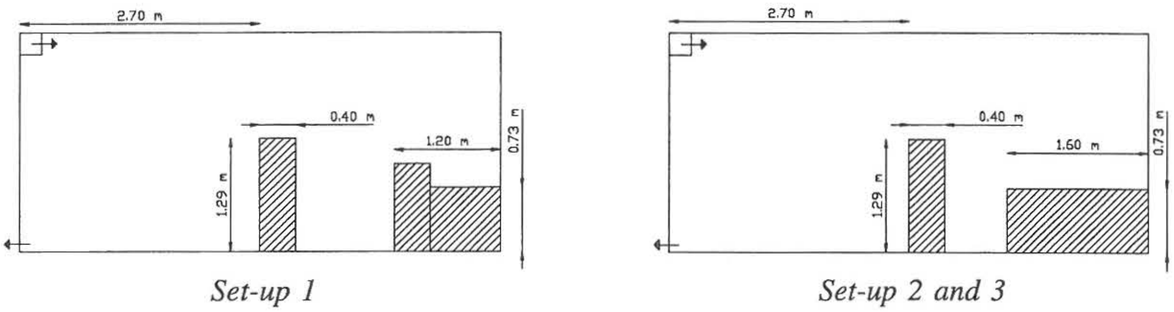


Figure 2.41 *The simulations of the three set-ups in figure 2.8 page 9. One simulation covers the experimental set-up 2 and 3.*

In the two simulations of the three experimental set-ups, the loss coefficient, f (see equation (2.4) page 34), of all the volume resistances is chosen to be identical. To determine the value of f, the velocity profile 2.00 m from the inlet is investigated. This location is chosen for the comparison because it is assumed that here the jet at the ceiling is fully developed and that the local influence from the furniture is negligible because the location is outside the furnished area. In this section the figures for the experiments with office furniture (see section 2.1.1.5) are repeated where it is found a help to the understanding.

At first the velocity profiles 2.00 m from the inlet are investigated to find a suitable value of f and afterwards the simulated flows in the rooms are compared with the ones found in the experiments.

Figure 2.43 shows the comparison between the velocity profiles 2.00 m from the inlet in the three experimental set-ups with office furniture and the two simulated set-ups with volume resistances. In the simulations f is chosen to 0.5 m^{-1}. The positive direction of the velocities is defined in figure 2.11 page 11.

The value of f equal to 0.5 m^{-1} is chosen because it is the most representative value of f. Figure 2.42 shows an example of different values of f.

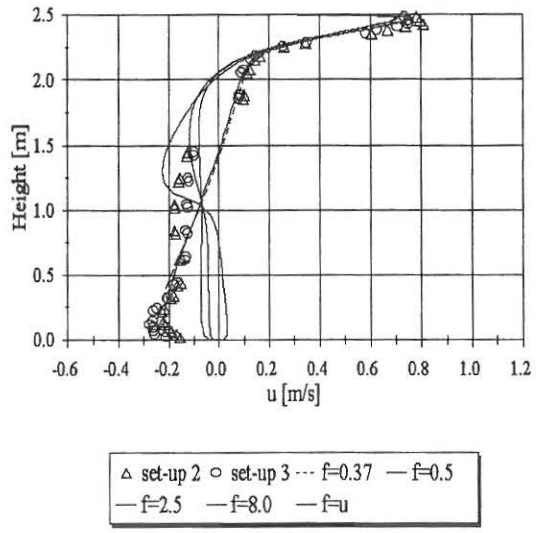
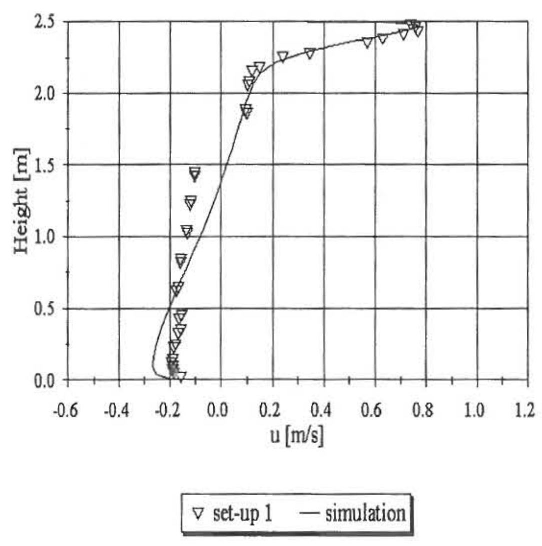


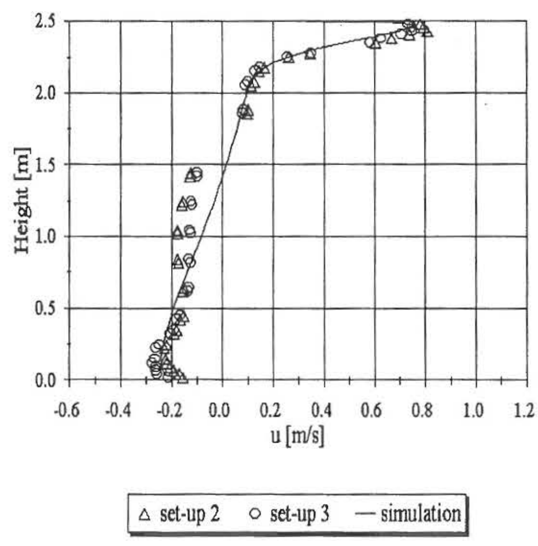
Figure 2.42 *Set-up 2 and 3 together with simulations with different values of f. f=u corresponds to a solid box.*

The figure shows that when f is large, the influence of the volume resistance on the velocity profile is significant. The difference between f equal to 0.37 m^{-1} and f equal to 0.5 m^{-1} is insignificant and f equal to 0.5 m^{-1} is chosen because it is the most suitable value in this case. This means that the value of f is approximately 0.5 m^{-1}.

Figure 2.43 shows the velocity profiles 2.00 m from the inlet in the three experimental set-ups and the simulation with f equal to 0.5 m^{-1}.



Set-up 1



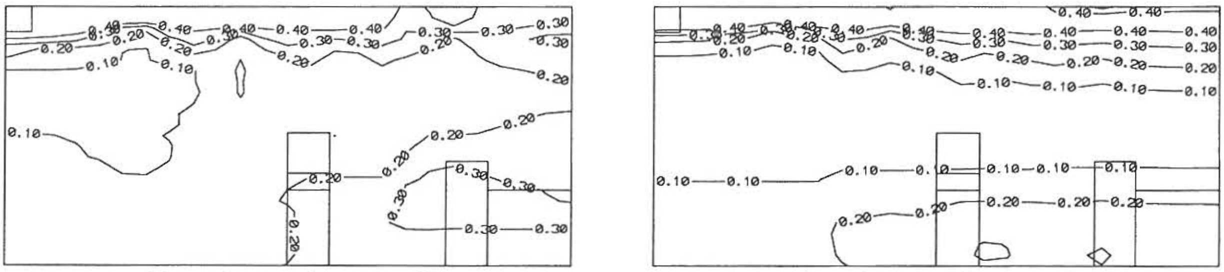
Set-up 2 and 3

Figure 2.43 *Comparison of the velocity profile 2.00 m from the inlet in the three set-ups. In the simulations f is equal to 0.5 m^{-1}.*

By studying figure 2.43 it is seen that in both cases the velocity profiles in the experimental and the simulated rooms are concordant in the upper part of the room. In the middle of the room, the measured velocity is higher than the simulated. At the floor, the simulated velocity in set-up 1 is higher than the measured whereas in set-up 2 and 3, the velocity profiles are almost identical. The differences in the velocity profiles are caused by the difference between the physical furniture and the volume resistances. In the experimental set-ups, the air is forced around the furniture whereas in the simulation, the air is disturbed equally over the whole volume. From figure 2.43 it can therefore be concluded that f equal to 0.5 m^{-1} is apparently a suitable common value for the simulation of office furniture.

The velocity level, the shape of the velocity profile, the velocity decay at the ceiling, the length scale and the maximum velocity in the occupied zone are also investigated to see if f equal to 0.5 m^{-1} is a suitable value for normal office furniture.

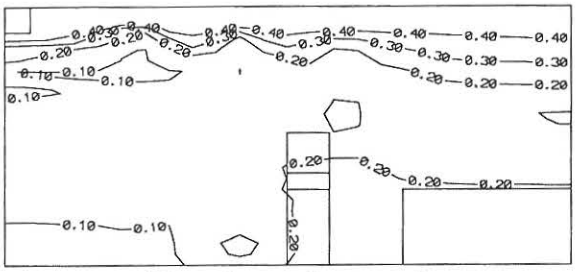
Figure 2.44 and 2.45 show the comparison of the velocity level in the experimental rooms with normal office furniture and in the simulated rooms with volume resistances where f is equal to 0.5 m^{-1}.



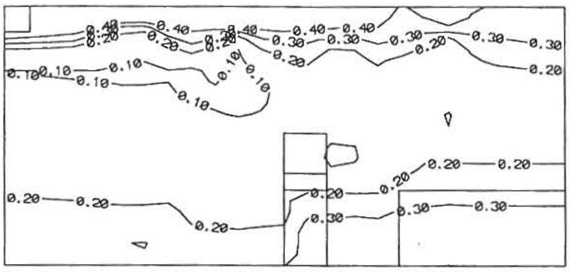
Experimental set-up 1 *Simulation of set-up 1*

Figure 2.44 *The velocity level in the experimental room with set-up 1 and in the simulated room with the same set-up. f is equal to 0.5 m^{-1}.*

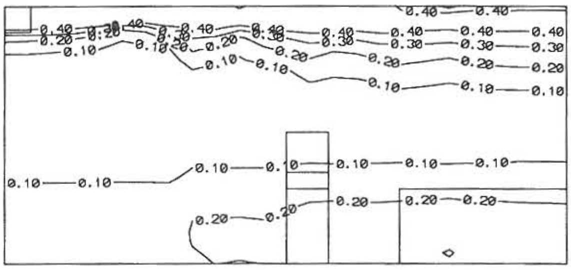
In figure 2.44 only velocities lower or equal to 0.40 m/s are shown. By comparing the simulation with the experiment, it is found that the velocity level at the ceiling is almost identical in the two rooms. At the floor, an area with 0.30 m/s is present in the experimental room and not in the simulated room. This difference is caused by the local physical influence of the furniture in the experimental set-up where the air is forced around the furniture whereas in the simulations, the volume resistances influence the air movements uniformly. By looking at the overall velocity level in the room, the simulation corresponds satisfyingly to the measurements.



Experimental set-up 2



Experimental set-up 3

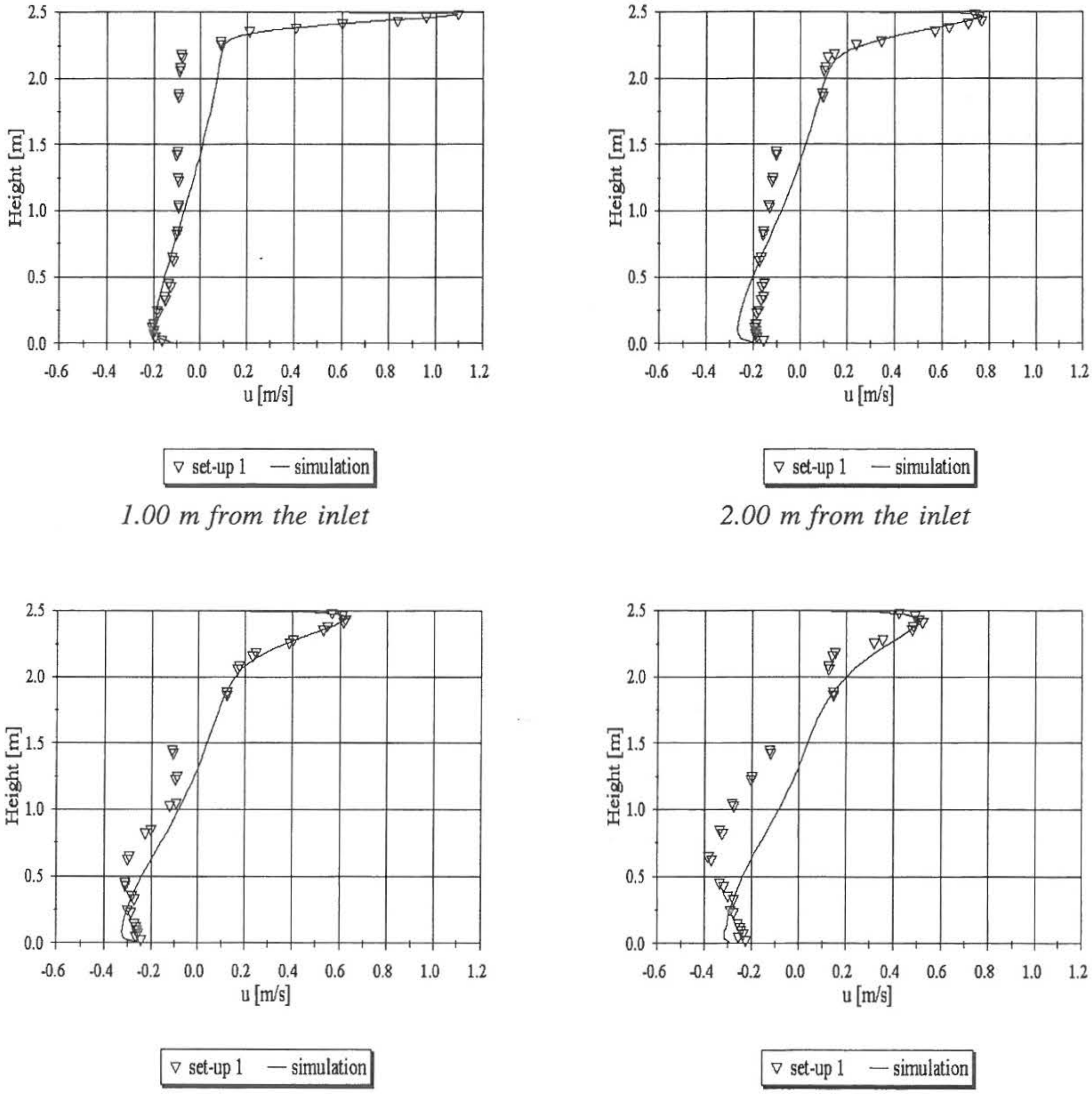


Common simulation of set-up 2 and 3

Figure 2.45 *The velocity level in the experimental rooms with set-up 2 and the and in the simulated room with the common set-up. f is equal to 0.5 m^{-1}.*

In figure 2.45 only velocities lower or equal to 0.40 m/s are shown like it was the case with set-up 1. By comparing the two experiments with the common simulation it is found that the velocity level at the ceiling is almost identical. At the floor, the velocity level in the simulated room corresponds satisfyingly with the two experiments when it is taken into consideration that in the experiments the physical furniture causes local disturbances to the flow whereas the volume resistances in the simulation make a uniform disturbance to the flow.

By studying the velocity level in the furnished rooms it is stated that a loss coefficient, f, equal to 0.5 m^{-1} is suitable for representing the office furniture. The velocity profiles 2.00 m from the inlet have already been investigated in figure 2.43. To see the difference between the local physical influence of the furniture on the velocity profile and the uniform disturbance to the flow caused by the volume resistance, the velocity profiles through the room are studied. The positive direction of the velocities is defined in figure 2.11 page 11.



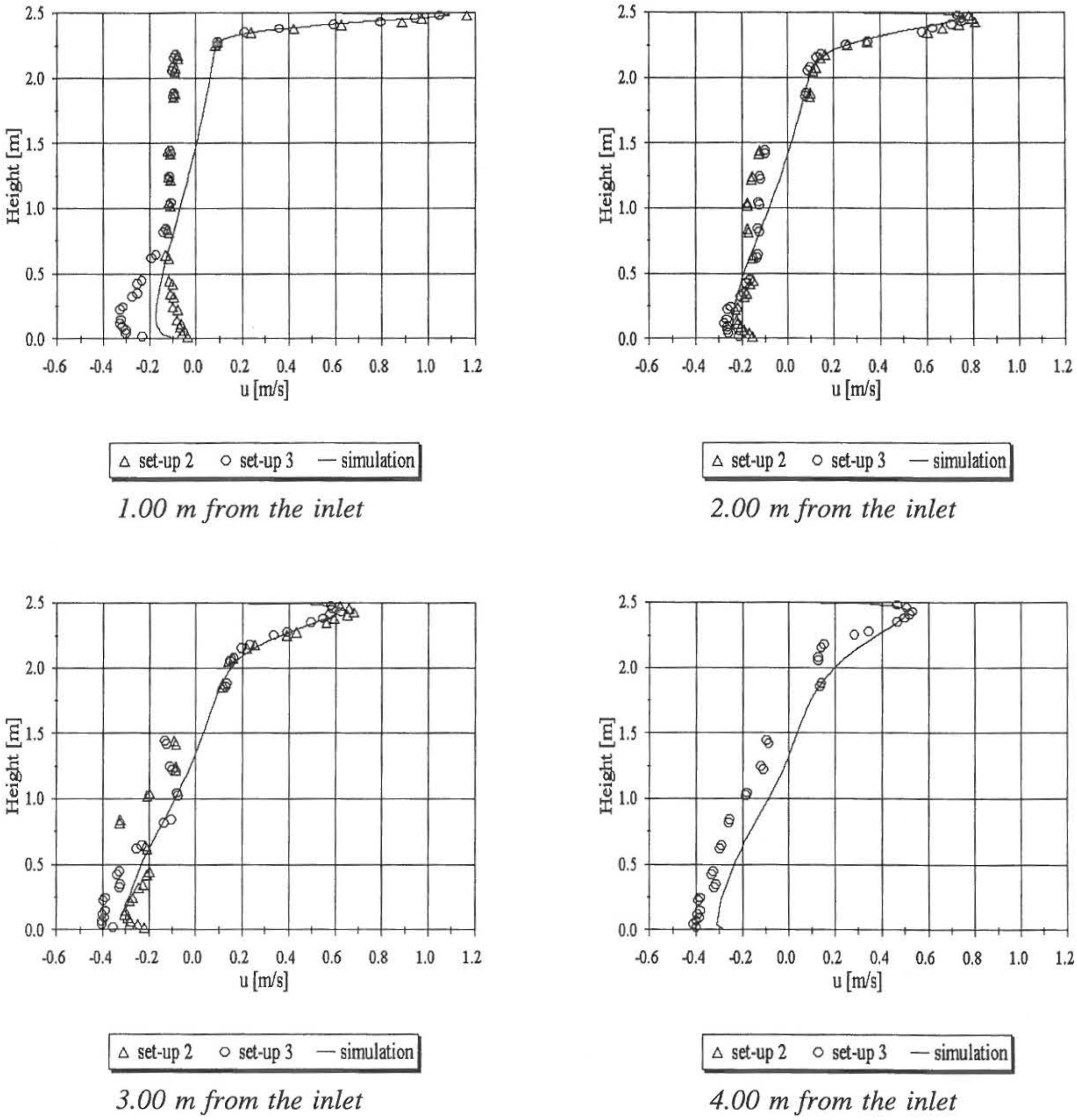
1.00 m from the inlet *2.00 m from the inlet*

3.00 m from the inlet *4.00 m from the inlet*

Figure 2.46 *The velocity profiles found 1.00, 2.00, 3.00 and 4.00 m from the inlet in the room with set-up 1 and in the simulation of the same set-up. f is equal to 0.5 m^{-1}.*

By studying the velocity profiles through the room in both the experimental set-up 1 and the simulation of the same with f equal to 0.5 m^{-1} it is found that at the ceiling the velocity profiles are almost identical. In the middle of the room some difference occurs between the experiment and the simulation. This is caused by the difference in using physical furniture and a volume resistance where the physical furniture affects the flow locally and the volume resistance influences the flow uniformly. At the floor the velocities are almost identical.

The following figure shows the velocity profiles through the room in the experimental set-up 2 and 3 and in the common simulation of the two with f equal to 0.5 m^{-1}.



1.00 m from the inlet

2.00 m from the inlet

3.00 m from the inlet

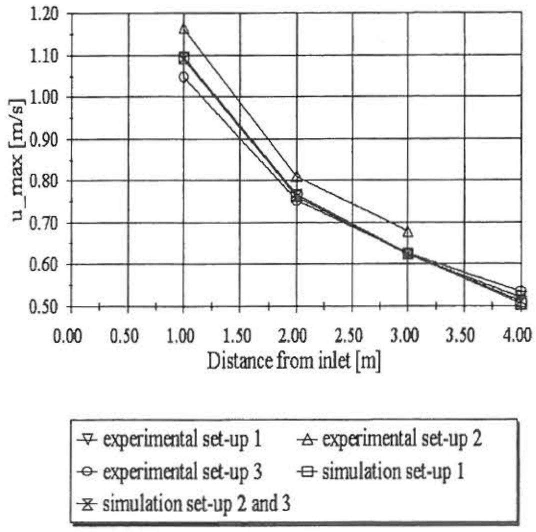
4.00 m from the inlet

Figure 2.47 *The velocity profiles found 1.00, 2.00, 3.00 and 4.00 m from the inlet in the room with set-up 2 and 3 and in the simulation of the common set-up. f is equal to 0.5 m^{-1}.*

The velocity profile 4.00 m from the inlet is not drawn for the experimental set-up 2 because at this location the desks are blocking for the measurements (see figure 2.8 page 9).

In the simulation of the set-up 2 and 3 good agreement between the velocity profiles at the ceiling is also found. On the other hand, at the floor some difference occurs which is caused by the earlier mentioned difference between physical furniture and a volume resistance and by the fact that the measurements are only made in the centre line of the room.

The study of the velocity profiles through the room shows good agreement between the experiments and the simulations with f equal to 0.5 m^{-1}. The flow at the ceiling is studied more closely by investigating and comparing the velocity decay, the length scale, the distance to the virtual origin and the individual constant of the diffuser, K_p.



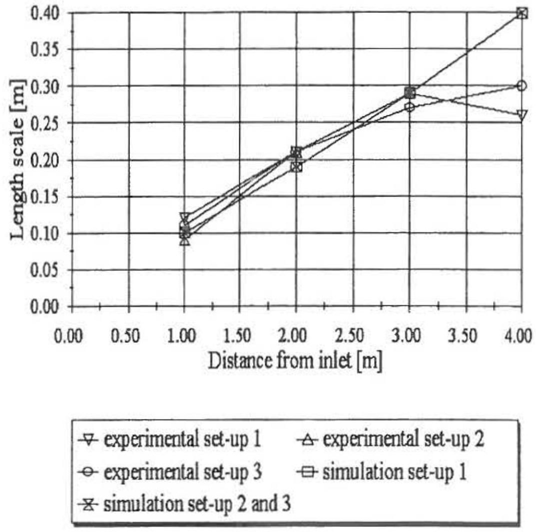


Figure 2.48 *The velocity decay under the ceiling to the left (u_{max} is the maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet.*

In figure 2.48 it is seen that the velocity decay at the ceiling and the length scale is almost identical in the three experiments with office furniture and in the two simulations with volume resistances where f is equal to 0.5 m^{-1}. Hereby, the simulations seem to fit the experiments, and if both the distance to the virtual origin and the individual constant of the diffuser are identical in the experiments and in the simulations, f equal to 0.5 m^{-1} is a suitable value for office furniture when the flow in the upper part of the room is considered.

The distance to the virtual origin, x_0, is identical in both the experiments and the simulations and it is found to 0.0 m which also is the value found in the experimental and simulated empty rooms. The individual constant of the diffuser, K_p, (see equation 2.2 page 16) is also identical in the experiments and in the simulations in both the empty rooms and in the furnished rooms and it is found to approximately 3.2. This means that the common loss coefficient, f, equal to 0.5 m^{-1} is suitable for the simulation of office furniture when the flow at the ceiling is investigated.

Another important value to investigate is the maximum velocity in the occupied zone. In the experiments (see section 2.1.1.5) it was found that furniture reduces the maximum velocity in the occupied zone compared with the empty room. In the simulations with the volume resistances almost the same velocity level was found in the lower part of the room as in the experiments with office furniture, in spite of the difference in the velocity profiles. Therefore, a reduction of the maximum velocity in the occupied zone is also to be expected in the simulated room with volume resistances. Table 2.4 shows the relation between the maximum velocity in the occupied zone of the furnished and the empty room for both the experiments and the simulations.

	Experiments				Simulations		
	empty room	set-up 1	set-up 2	set-up 3	empty room	set-up 1	set-up 2 and 3
u_{rm} [m/s]	0.557	0.383	0.343	0.410	0.381	0.324	0.310
$u_{rm}/u_{rm,0}$		0.69	0.62	0.74		0.85	0.81

Table 2.4 *The maximum velocity in the occupied zone in the experiments and the simulations of the empty and the furnished rooms ($u_{rm,0}$ and u_{rm} respectively). f is equal to 0.5 m^{-1} in the simulated furnished rooms.*

The table shows that the reduction in the maximum velocity in the occupied zone is larger in the experiments than in the simulations. This difference is mainly caused by the difference in the velocity in the empty rooms because the velocities in the furnished rooms are almost similar in spite of the difference in the influence on the flow in the room caused by the physical furniture and the volume resistances.

On the basis of the investigations made in this section, a loss coefficient, f, equal to 0.5 m^{-1} is found to be satisfying for the simulation of office furniture. In the following simulations f equal to 0.5 m^{-1} will be used and a volume resistance with this value of f will be named a furniture volume.

2.2.1.3 Further Simulations of the Room

In the experiments (see section 2.1.1.5) and in the simulations (see section 2.2.1.2) were found that office furniture in a room does not influence the jet under the ceiling whereas the maximum velocity in the occupied zone is reduced by the furniture. These conclusions were also made on the basis of the experiments made with the 3-dimensional slot inlet and the two radial jets with swirl (see section 2.1.2.5 and 2.1.3.5). In the previous section it was found that 2-dimensional simulations with a volume resistance with a loss coefficient, f, equal to 0.5 m^{-1} corresponds to office furniture. To investigate the conclusions found earlier more closely, further simulations are made with the 2-dimensional slot inlet. It is studied how the location and the size (height and length) of the furniture (volume) influences the flow in the upper part of the room, the maximum velocity in the occupied zone and the momentum flow in the room. Furthermore, the importance of the number of groups of furniture is investigated. Simulations are also made in a shorter and a longer room to see if the length of the room has any influence on the conclusions found earlier.

In the simulations in the room with the length of the physical room (5.40 m) the furniture volume is mainly located in the half of the room opposite the inlet like the physical office furniture in the experiments. Figure 2.49 shows the locations of the furniture volumes in the half of the room opposite the inlet.

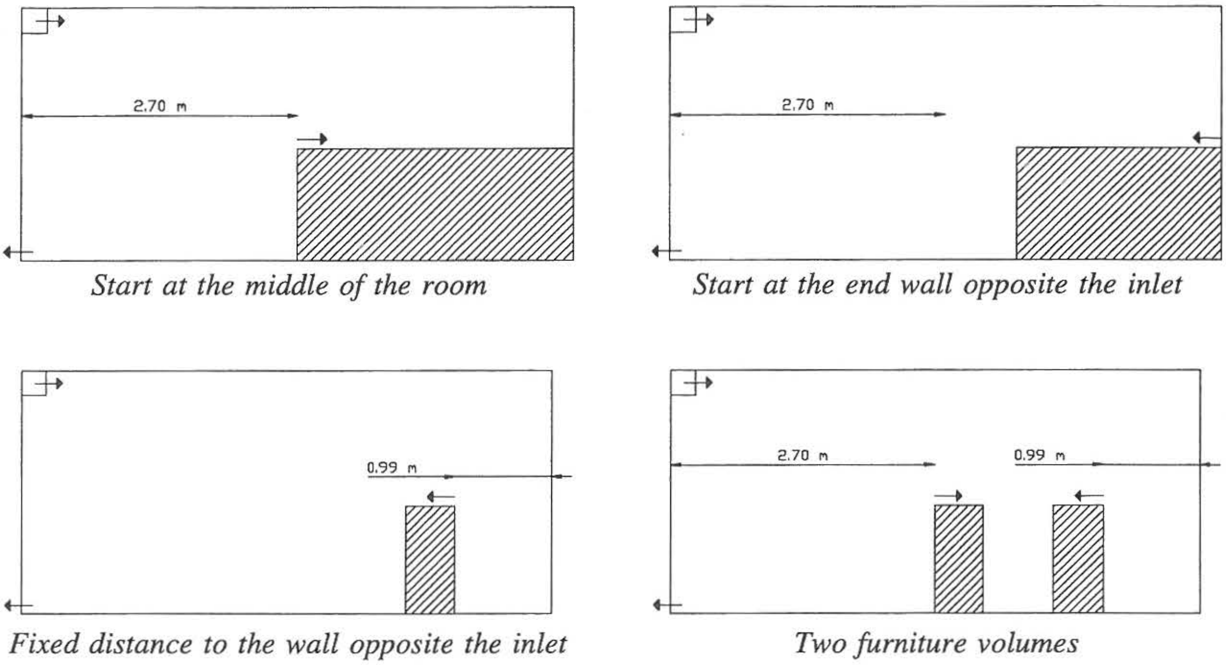


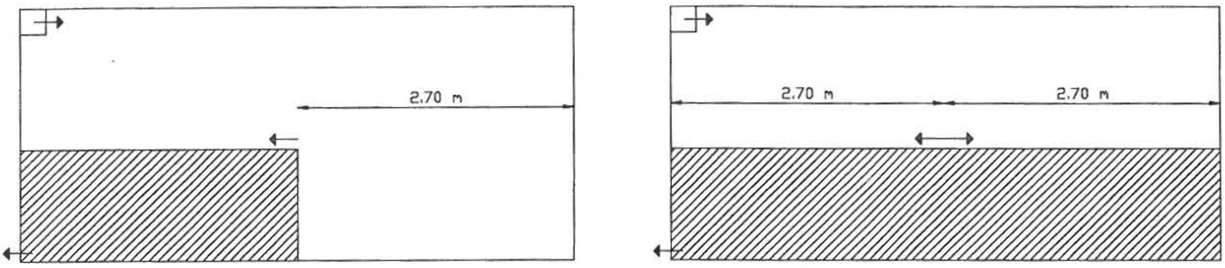
Figure 2.49 *The location of the furniture volumes in the half of the room opposite the inlet. The arrows show the direction of growth of the furniture volumes.*

The upper left corner of figure 2.49 shows a furniture volume starting at the middle of the room and this end of the furniture volume is fixed. This set-up is simulated with a 0.25, 0.50, 0.75, 1.71 and 2.70 m long furniture volume and all the lengths are simulated with the heights 0.50, 0.75, 1.10, 1.80 and 2.00 m.

In the upper right corner of figure 2.49 a furniture volume adjoining the end wall opposite the inlet is shown. This furniture volume is simulated with lengths per 0.25 m going from 0.25 to 2.00 m. The simulations are all made with a 1.10 m high furniture volume.

The lower part of figure 2.49 shows one and two furniture volumes where a fixed distance to the end wall opposite the inlet is maintained. The second furniture volume in the lower right corner of figure 2.49 is fixed at the middle of the room. In the room with two furniture volumes, the length of the volumes is identical. In both situations the furniture volume is simulated with the lengths 0.25, 0.50 and 0.75 m and all the lengths are simulated with the heights 0.50, 0.75, 1.10, 1.80 and 2.00 m.

Simulations are also made where the furniture volume is only present in the half of the room with the inlet and where the furniture volume is located in both halves of the room. Only two simulations with each set-up are made because it is found more interesting to investigate the consequences when the furniture volume is located close to the area of the maximum velocity in the occupied zone /7/, /27/, /28/ and /30/.



Start at the middle of the room *Symmetry about the middle of the room*

Figure 2.50 *The location of the furniture volumes in the half of the room where the inlet is and in both halves of the room. The arrows show the direction of growth of the furniture volumes.*

In figure 2.50 to the left, the furniture volume is starting at the middle of the room and this end of the furniture volume is fixed. The simulated lengths are 1.71 and 2.70 m and the height is 1.10 m. In the situation with two furniture volumes placed symmetrically about the middle of the room, the total length of the furniture volume is 3.42 and 5.40 m (2×1.71 m and 2×2.70 m, respectively) and the height is 1.10 m in both cases.

Some of the simulations made in the room with the length of the physical room (5.40 m) are also made in a shorter and a longer room. In both these rooms, the inlet is identical to the one used in the 5.40 m long room and the inlet velocity is also kept at 3.47 m/s. The short room is 3.75 m and the long room is 7.50 m. This corresponds to 1.5H and 3.0H, respectively where H is the height of the room. Before simulations with furniture volumes are made in the two rooms, the empty rooms are simulated to find the reference conditions.

In the simulations with the furniture volume in the short and the long room only 1.10 m high furniture volumes are used. The simulations made in the two rooms are equivalent with the simulations made in the 5.40 m long room in that way that the distance between the end wall opposite the inlet and the end of the furniture volume is fixed (see figure 2.51).

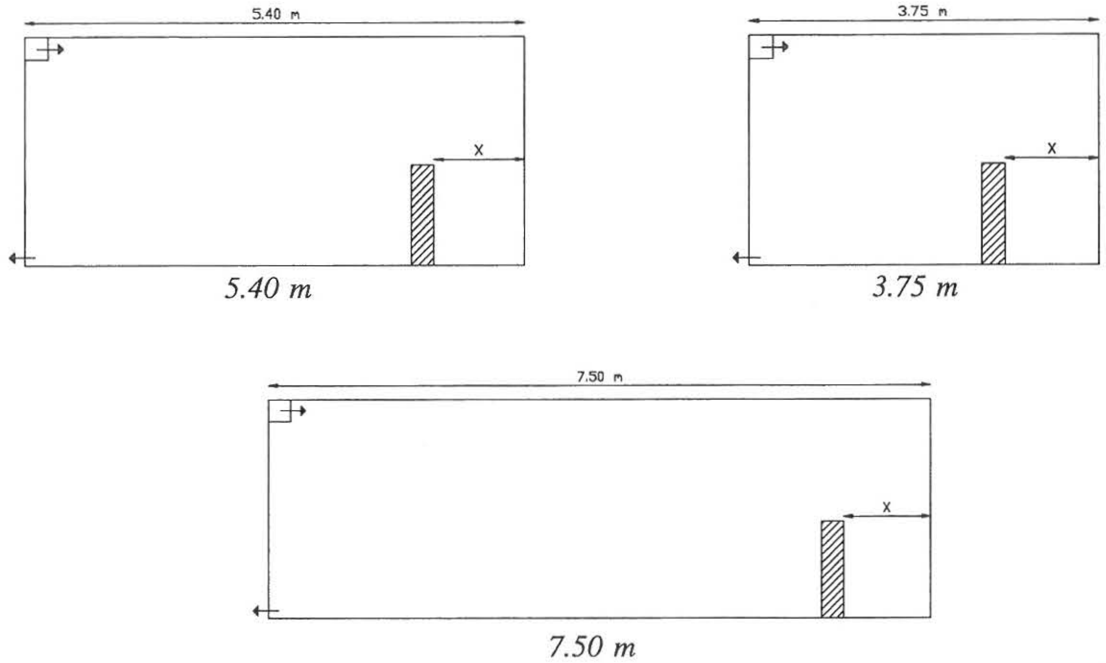


Figure 2.51 *An example of the location of the same furniture volume in the 5.40, 3.75 and 7.50 m long room.*

The simulated set-ups in the short and the long room are the ones shown in figure 2.49 except for the one in the upper right corner. Because the length of the furniture volume is not changed, the furniture volumes are mostly present in both halves of the room in the 3.75 m long room whereas in the 7.50 m long room it is only present in the half of the room opposite the inlet.

The discussion of the results found in the simulations mentioned here is made in section 2.3 together with the discussion of the results found in the experiments and the simulations of the 3-dimensional slot inlet and the two radial jets with swirl (see section 2.1.2, 2.1.3, 2.2.2 and 2.2.3). In this way all the results are taken into account when the conclusions are made. The discussion of the results in section 2.3 consists of an investigation of the jet under the ceiling and a study of the maximum velocity in the occupied zone where a method for the determination of this velocity is developed. Furthermore, the influence of the office furniture on the momentum flow in the room is studied.

In the next sections the simulations of the experiments with the 3-dimensional slot inlet and the two radial jets with swirl are described. It is tested if the furniture volume with a loss coefficient, f, equal to 0.5 m^{-1} also is suitable for the office furniture in these two cases.

2.2.2 Simulations with the 3-dimensional Slot Inlet

In the room with the 3-dimensional slot inlet only the empty room and the experimental set-up with office furniture is simulated. The simulations of this inlet are 3-dimensional. At first the simulated empty room must be concordant to the experimental empty room. When this is achieved, the furnished room is simulated with the furniture volume (the loss coefficient, f, is equal to 0.5 m^{-1}).

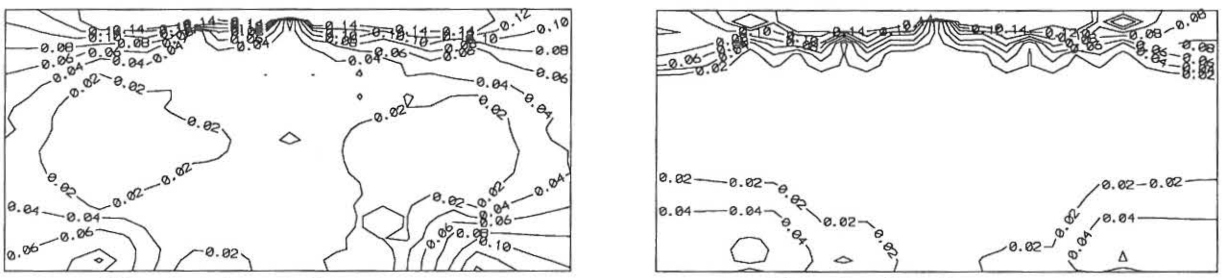
2.2.2.1 The Empty Room

The flow in the simulated empty room must be similar to the flow in the experimental empty room. To evaluate the simulation, the velocity level, the shape of the velocity profile, the velocity decay at the ceiling, the length scale and the maximum velocity in the occupied zone are studied.

In the investigations of the simulated room, the velocities are extracted at the same locations as in the experiments (see figure 2.18 page 18) and the average value across the room is used. The figures of the experimental empty room are repeated where it is found a help for the understanding.

In the simulations, the inlet and the exhausts are constructed so that they are identical to the physical ones (see section 2.1.2). The angle of which the air is injected into the room is in the simulations 42° whereas the angle is approximately 45° in the experiments. This new value of the angle is chosen because hereby, the generated wall jet is identical with the wall jet measured at the ceiling. Like it was the case in the simulations with the 2-dimensional slot inlet, it is more important that the velocity decay at the ceiling is concordant in the two rooms than that the flow in the lower part of the rooms is identical. The grid distribution is (LxHxW) 94x42x38 cells where the grid distance is smaller close to the walls and the inlet than in the middle of the room.

The investigations of the simulated empty room begin with the comparison of the velocity level in the two rooms (see figure 2.52)

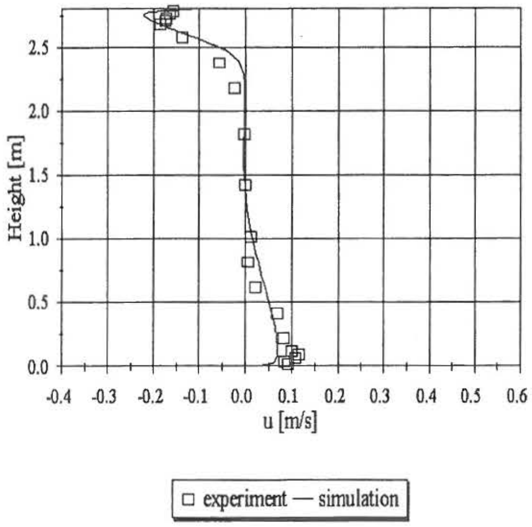


The experimental empty room *The simulated empty room*

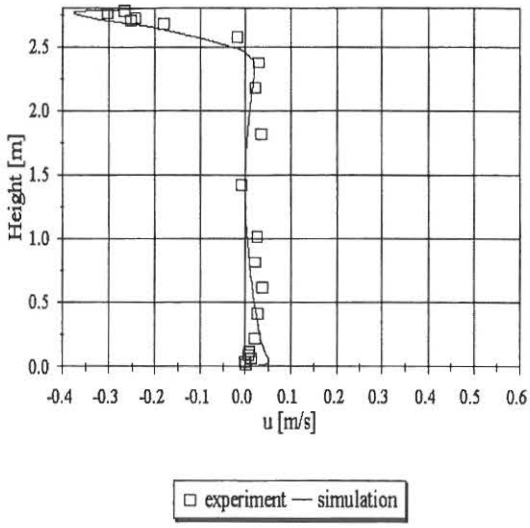
Figure 2.52 The velocity level in the experimental and simulated empty room.

In figure 2.52 only velocities equal to or lower than 0.14 m/s are shown. By studying the figure it is seen that the velocity level in the two rooms is similar. At the floor, the velocity level in the simulated empty room is lower than the velocity level in the physical empty room. This pattern was also found in the room with the 2-dimensional slot inlet (see figure 2.38 page 35). As mentioned earlier, it is more important that the flow at the ceiling is identical in the two rooms than that the flow in the lower part of the room is concordant. This choice is made because at the ceiling the jet is undisturbed.

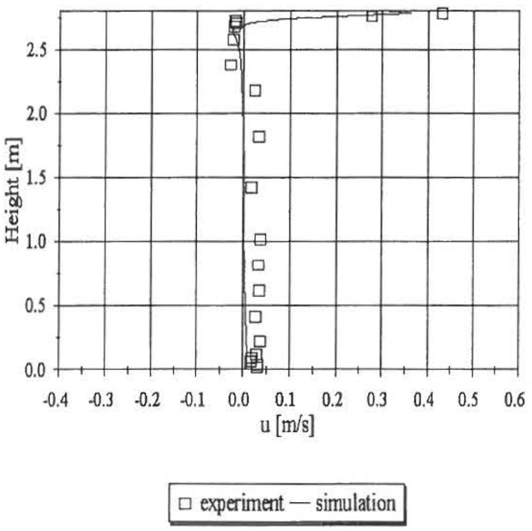
The difference in the velocity level at the floor is investigated closer by comparing the velocity profiles through the two rooms. The average velocity profiles 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the experimental and the simulated empty room are shown in figure 2.53. The positive direction of the velocities is defined in figure 2.25 page 22.



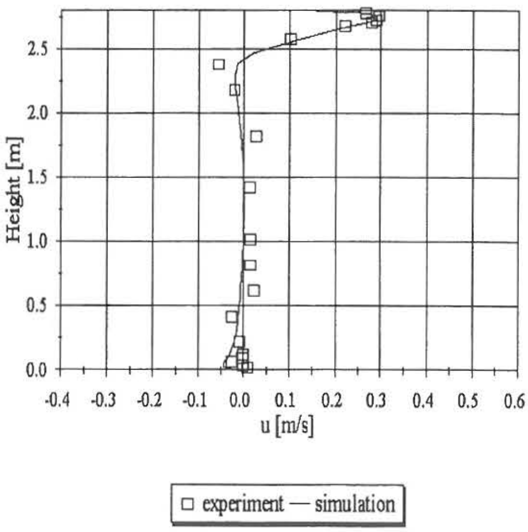
1.00 m from the end wall



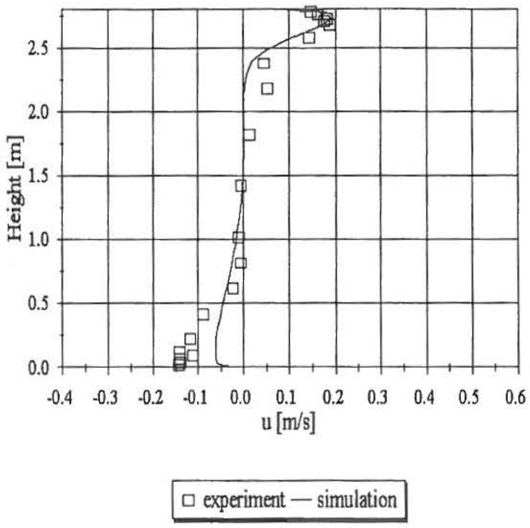
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



5.00 m from the end wall

Figure 2.53 *The average velocity profiles 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with the 3-dimensional slot inlet. The slot inlet is located 2.90 m from the left end wall.*

In figure 2.53 is seen that the velocity profiles at the ceiling in the simulated and the experimental empty room are similar. This is also the case in the middle of the room. At the floor, the experiment show a higher velocity close to the end wall than the simulation. This picture is reversed in the middle part of the room. As mentioned before, the jet at the ceiling is of most importance so the velocity decay, the length scale, the distance to the virtual origin and the individual constant of the diffuser are compared in the experimental and the simulated empty room.

Figure 2.54 shows the comparison of the velocity decay at the ceiling and the length scale. The maximum velocity, u_{max}, is shown as the absolute value. In the figure the velocities are found on both sides of the inlet.

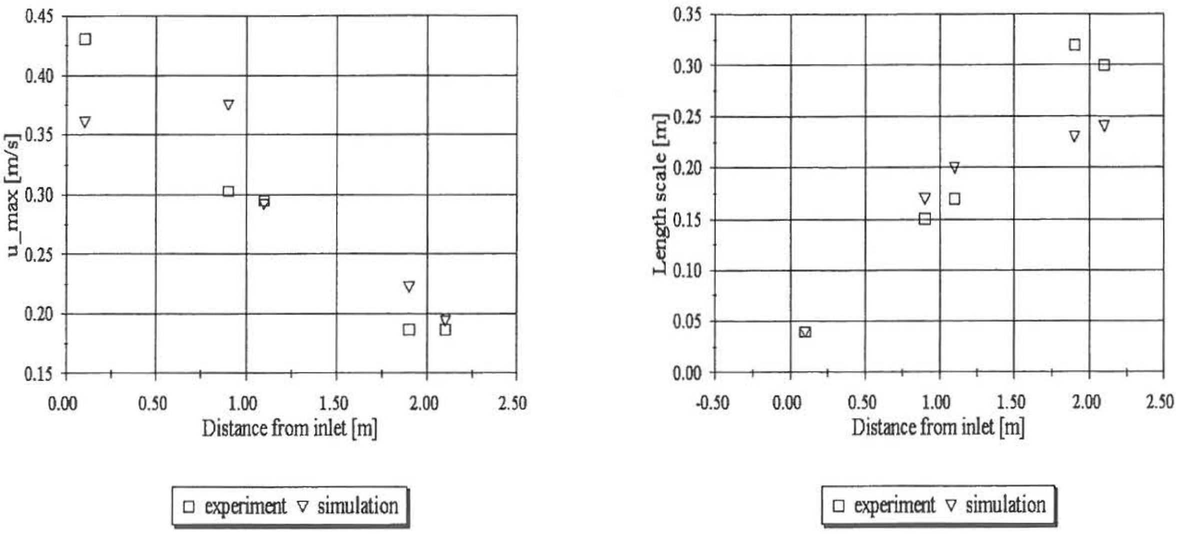


Figure 2.54 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The 3-dimensional slot inlet is located 2.90 m from the left end wall.*

In the figure it is seen that the velocity decay is similar far from the inlet whereas close to the inlet some deviation occurs. This can be caused by the difference in the physical and the simulated inlet which results in a different development at the beginning of the jet. As seen from figure 2.54, this difference is equalized when the jet is fully developed. The length scale in the two rooms shows an opposite behaviour where it is similar close to the inlet and different far from the inlet. These conflicting results indicate that the simulated jet under the ceiling is acceptable. To ensure this, the distance to the virtual origin, x_0, and the individual constant of the diffuser, K_p, are investigated.

The distance to the virtual origin is found where the regression line in figure 2.54 to the right intersects with the x-axis. In both the experimental and the simulated empty room, x_0 is found to 0.35 m. The individual constant of the diffuser is found from equation (2.2) (see section 2.1.1.5 page 16). K_p is approximately 1.3 in both the physical and the simulated empty room.

A parameter of interest is also the maximum velocity in the occupied zone of the room. The velocity profiles (figure 2.53) showed that it varies which situation has the largest velocity at the floor. The maximum velocity in the occupied zone of the experimental empty room is 0.142 m/s and in the simulated empty room it is 0.069 m/s. Hereby, the experiment has the largest velocity which also was the case in the room with the 2-dimensional slot inlet.

On the basis of the investigations made in this section it can be concluded that the modelling of the room with the 3-dimensional slot inlet is satisfying, even though the difference in maximum velcoity is significant. This model of the physical room is used in the simulation of the room with office furniture present.

2.2.2.2 The Room with Office Furniture

In the 3-dimensional simulation of the set-up with normal office furniture in the room with the 3-dimensional slot inlet, the construction of the simulated empty room is used together with furniture volumes (the loss coefficient, f, is equal to 0-5 m^{-1}). As mentioned earlier, the furniture volumes in the 3-dimensional simulation have the same size and location as the physical furniture. In the simulation the furniture volumes are used because it is tested if the common loss coefficient for normal office furniture found in the 2-dimensional simulations with the 2-dimensional slot inlet (see section 2.2.1.2) also is valid in the simulation with the 3-dimensional slot inlet. In the present simulation, the set-up from figure 2.22 page 20 is simulated and figure 2.55 shows the simulated set-up with furniture volumes.

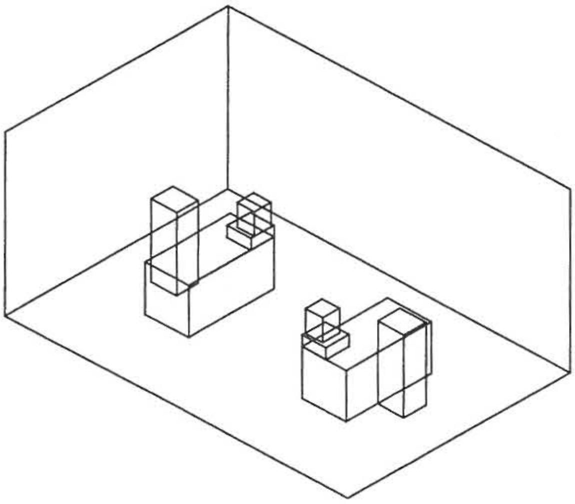
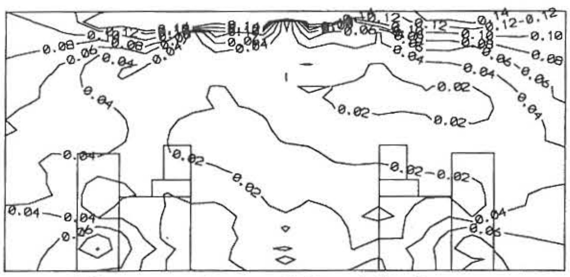
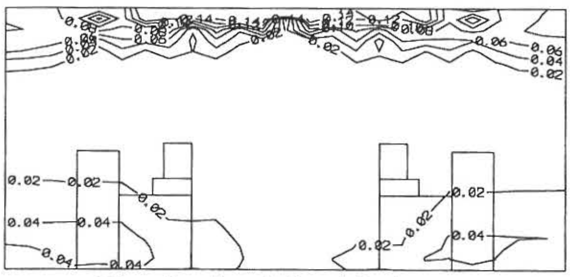


Figure 2.55 The simulation of the physical set-up with office furniture.

In the investigations of the simulation, the velocity level, the velocity profiles, the velocity decay at the ceiling, the length scale, the distance to the virtual origin and the individual constant of the diffuser are compared in the experimental and the simulated furnished room. At first, the velocity level in the two rooms is compared (see figure 2.56).



The experimental furnished room

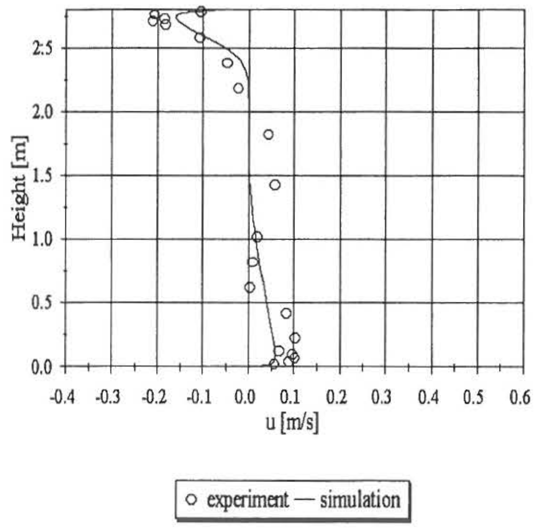


The simulated furnished room

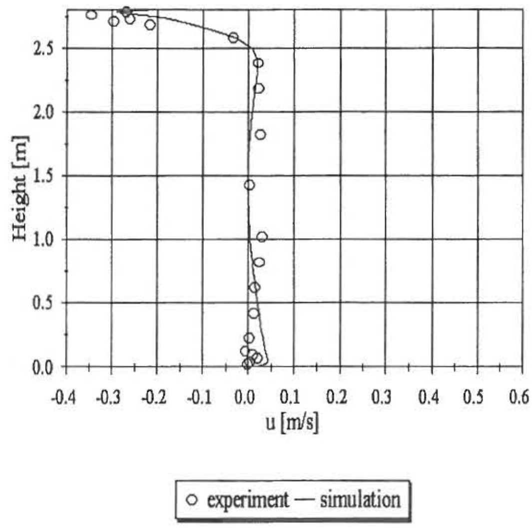
Figure 2.56 The velocity level in the experimental and simulated furnished room.

In figure 2.56 only velocities equal to or lower than 0.14 m/s are shown. By comparing the two rooms it is found that the velocity level in the upper part of the room is similar in the physical and the simulated furnished room. In the floor area, the velocity level in the simulated furnished room is lower than in the experimental furnished room. This was also found in the comparison of the experimental empty room and the simulated empty room (see figure 2.52 page 49). Apparently, the furniture volume seems to represent the office furniture satisfyingly.

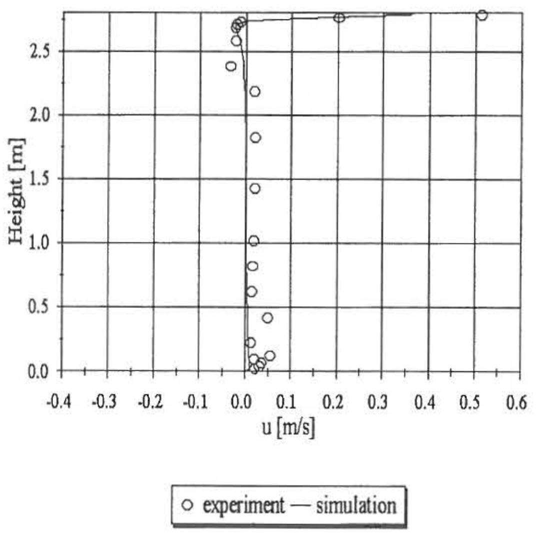
The investigations are continued with the comparison of the velocity profiles through the physical and the simulated room. The positive direction of the velocities is defined in figure 2.25 page 22.



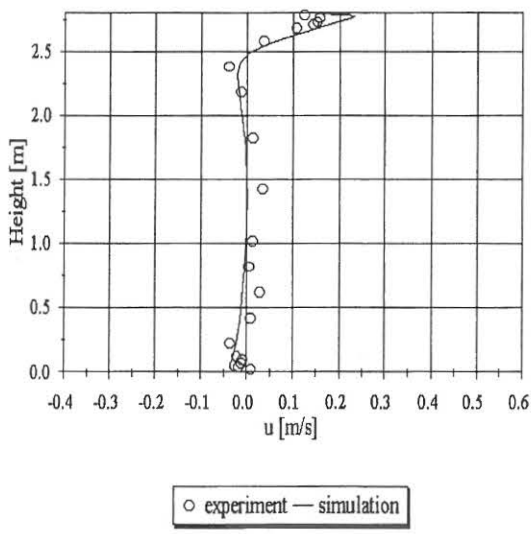
1.00 m from the end wall



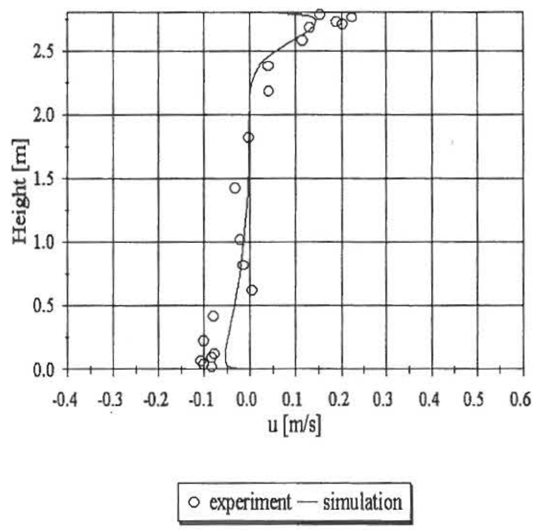
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



5.00 m from the end wall

Figure 2.57 *The average velocity profiles 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the furnished room with the 3-dimensional slot inlet. The slot inlet is located 2.90 m from the left end wall.*

The investigations of the velocity profiles through the two furnished rooms show that the simulated jet at the ceiling is reduced compared with the measured jet. This can mean that the furniture volumes are not suitable for the simulation of normal office furniture in other cases than in the room with the 2-dimensional slot inlet. The reason for this is that in the experiments with the office furniture no influence on the jet under the ceiling was found (see section 2.1.2.5) and the reduced velocity in the simulation can indicate a disturbance of the jet. This will be examined more closely in the following investigations. At the floor, the simulation seems to correspond to the experiment when it is taken into account that an average value of the velocity across the room is used and that the physical furniture affects the air movements in the room differently than the furniture volumes.

As mentioned above, the jet under ceiling needs to be examined closer to see if the furniture volume is suitable for the simulation of normal office furniture. In the examination, the velocity decay, the length scale, the distance to the virtual origin and the individual constant of the diffuser are studied. Figure 2.58 shows the velocity decay at the ceiling and the length scale in the experimental and the simulated furnished room.

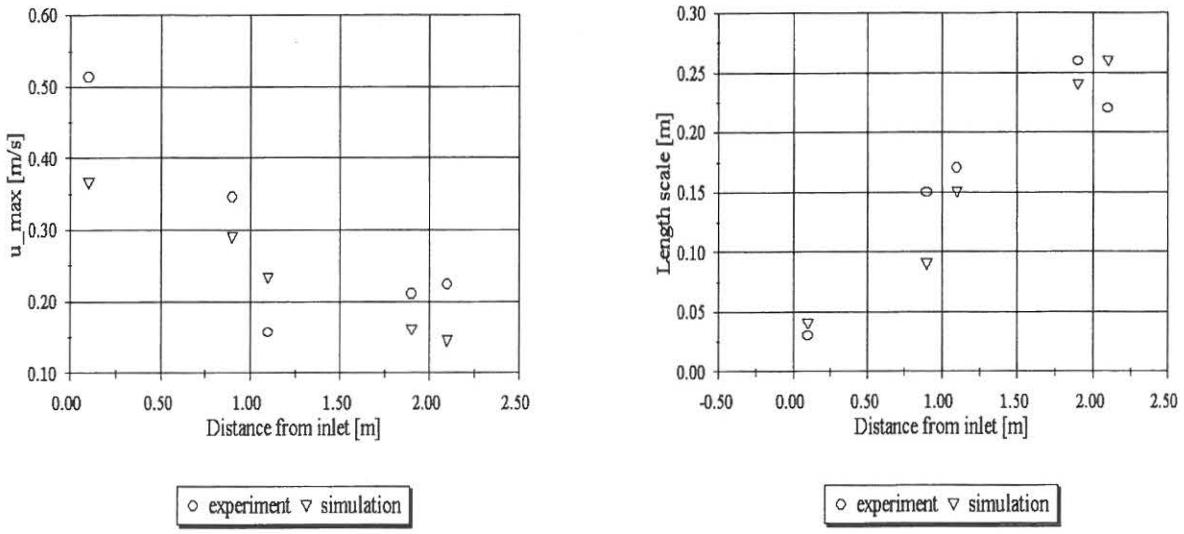


Figure 2.58 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The 3-dimensional slot inlet is located 2.90 m from the left end wall.*

By studying the velocity decay in the room with the 3-dimensional slot inlet it is found that the simulated velocity is lower than the measured velocity (except 1.10 m from the inlet). The exception could be caused by a wrongly measured velocity so that the maximum velocity is not found because of the distance between the measuring points. The velocity decay shows the same as was found by studying the velocity profiles through the room. Close to the inlet, the difference in u_{max} is most clearly and it probably comes from the different modelling of the inlet in the experiment and the simulation because this difference was also found in the comparison of the empty rooms (see figure 2.54 page 52). Contrary to this, the comparison of the length scale in the two rooms shows good agreement. The result of this examination is, that it is still not possible to either accept or reject the furniture volume as a representative for normal office furniture. The distance to the virtual origin and the individual constant of the diffuser are now examined so that the use of the furniture volume better can be evaluated.

In both the experiment and the simulation the distance to the virtual origin is found to 0.35 m which also was the case in the corresponding empty rooms. Hereby, the furniture volume seems to be able to replace the normal office furniture. The individual constant of the diffuser, K_p is found from equation (2.2) page 16 and it is approximately 1.2 in the simulation of the furnished room. This value is not the one found in the experiment with office furniture where K_p is approximately 1.3. The difference in K_p means that the simulated value is 8% lower than the measured value.

Another important parameter to investigate is the maximum velocity in the occupied zone of the room. In both the empty and the furnished room it was found that the velocity level at the floor in the simulated room is lower than in the experimental room. In the experiments and simulations with the 2-dimensional slot inlet and in the experiments with both the 3-dimensional slot inlet and the two radial jets with swirl it was found that furniture reduces the maximum velocity in the occupied zone. Table 2.5 shows the maximum velocity in the occupied zone in both the experimental and the simulated room with office furniture.

	Experiment		Simulation	
	empty room	furnished room	empty room	furnished room
u_{rm} [m/s]	0.142	0.106	0.069	0.058
$u_{rm}/u_{rm,0}$		0.75		0.84

Table 2.5 *The maximum velocity in the occupied zone in the experiment and the simulation of the empty and the furnished room ($u_{rm,0}$ and u_{rm} respectively).*

The table shows that the simulated reduction of the maximum velocity in the occupied zone is smaller than the measured one. This is caused by the difference in the way the physical furniture and the furniture volume affects the air flow. The physical furniture forces the air to go around it and thereby creates a local disturbance whereas the furniture volume is porous and it disturbs the air uniformly. The difference in the reduction of velocity was also found in the simulations of the 2-dimensional slot inlet and it has almost the same size.

On the basis of the investigation made in this section concerning if it is possible to use the furniture volume to represent normal office furniture in the room with the 3-dimensional slot inlet it is found that the furniture volume is suitable for the simulation in spite of that the individual constant of the diffuser did not correspond to the measured one. The reason for accepting the furniture volume is that all the other parameters investigated did not show any deviation from the measurements with normal office furniture.

In the next section it is investigated if the furniture volume also is suitable for the simulation of office furniture in the room with the two radial jets with swirl.

2.2.3 Simulations with the Two Radial Jets with Swirl

In the room with the two radial jets with swirl a 3-dimensional simulation is made of the empty and the furnished room. In the furnished room, furniture volumes (the loss coefficient, f, is equal to 0.5 m^{-1}) are inserted instead of the physical furniture like it was the case with both the 2-dimensional and the 3-dimensional slot inlet. Before the simulation with the furniture volumes is made, the simulated empty room has to correspond to the experimental empty room.

2.2.3.1 The Empty Room

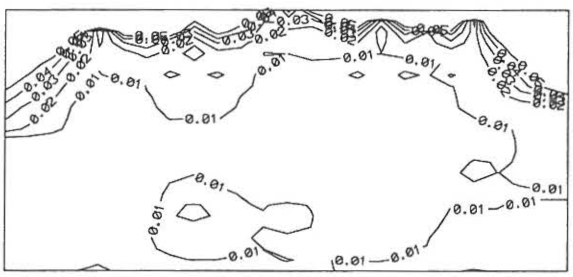
The air movements in the simulated empty room must be similar to the air movements in the experimental empty room. To evaluate the simulation, the velocity level, the shape of the velocity profile, the velocity decay at the ceiling, the length scale and the maximum velocity in the occupied zone are studied.

In the investigations of the simulated room, the velocities are extracted at the same locations as in the experiments (see figure 2.29 page 26) and the average value across the room is used. The figures of the experimental empty room are repeated where it is found a help for the understanding.

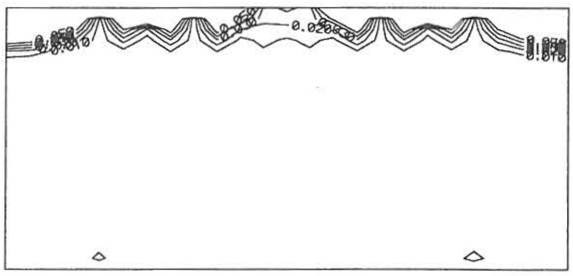
In the simulation of the room with the two radial jets with swirl the exhausts are constructed so that they are identical to the physical ones (see section 2.1.3). The physical inlet is circular and this cannot be constructed in the used CFD program, Flovent, which only allows rectangular geometries. Therefore, a quadrilateral inlet is constructed with the same effective area as the physical inlet. The physical inlet creates a rotating jet at the beginning that almost immediately is transformed into a radial jet along the ceiling. In order to simulate this type of inlet the flow pattern has been changed (see figure 2.59) and it has been necessary to halve the inlet flow and the exhausted air. This is done because in this way the flow in the room is similar to the physical flow (as will be shown later) and it also compensates for the loss in momentum the physical inlet creates. The changes from the physical to the simulated inlet are acceptable because the flow and the velocities in the experimental and the simulated room are similar and because the momentum by that also is similar. The grid distribution is (L×H×W) 94×39×60 cells where the grid distance is smaller close to the walls and the inlet than in the middle of the room.

Figure 2.59 *The physical circular inlet and the simulated quadrilateral inlet.*

At first the overall velocity level in the two rooms is compared (see figure 2.60).



The experimental empty room

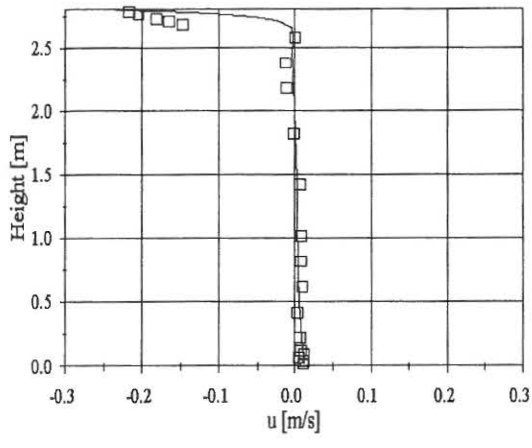


The simulated empty room

Figure 2.60 *The velocity level in the experimental and simulated empty room.*

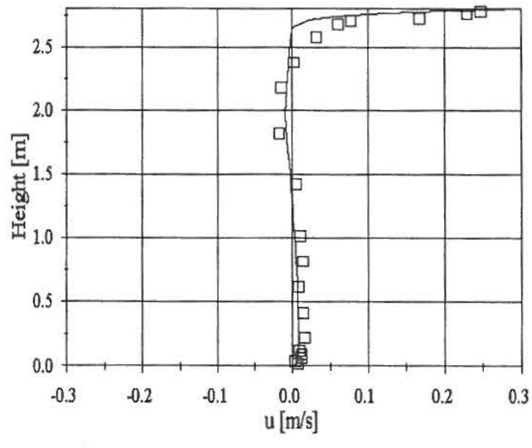
In figure 2.60 only velocities lower than or equal to 0.05 m/s are shown. At the ceiling the experiment and the simulation show good agreement whereas in the lower part of the room some difference occurs. It is seen that in the experimental room a velocity level of 0.01 m/s is present whereas no velocity is visible in the simulated room. This is not a critical deviation because in both rooms the air in the occupied zone is almost stagnant. Furthermore, this low value is only the interpolated velocity and not the measured velocity because the anemometer can measure in this area.

From the investigations of the velocity level in the room it is found that the simulated inlet and by that the air flow in the room corresponds to the physical conditions. This is investigated further by studying the velocity profiles through the room (see figure 2.61). The positive direction of the velocities is defined in figure 2.25 page 22.



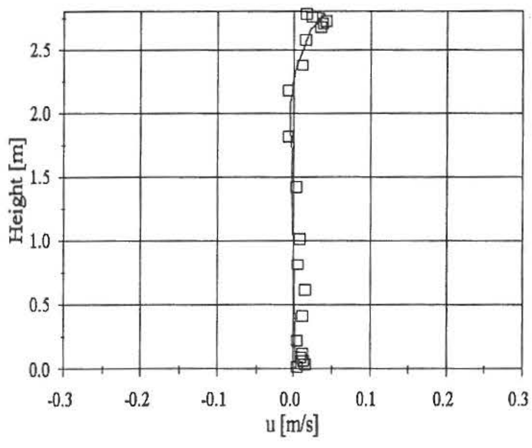
□ experiment — simulation

1.00 m from the end wall



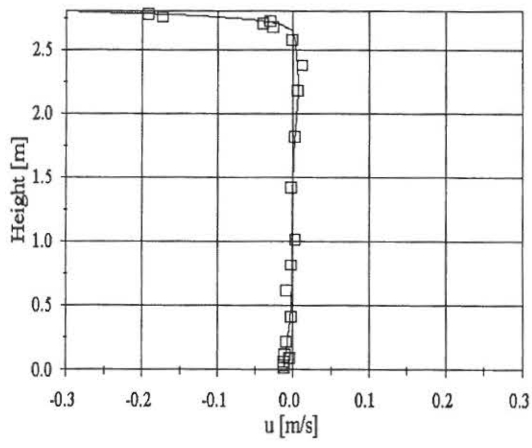
□ experiment — simulation

2.00 m from the end wall



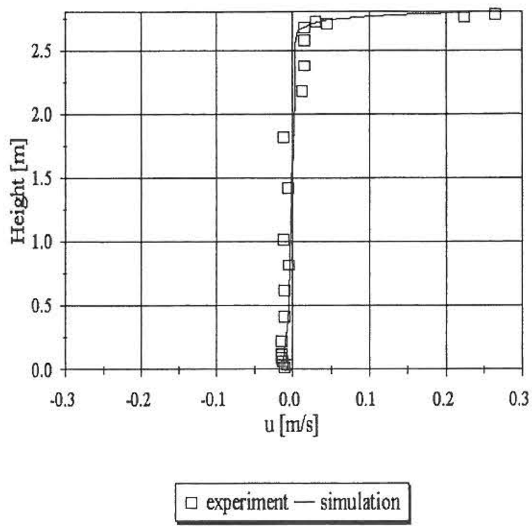
□ experiment — simulation

3.00 m from the end wall



□ experiment — simulation

4.00 m from the end wall

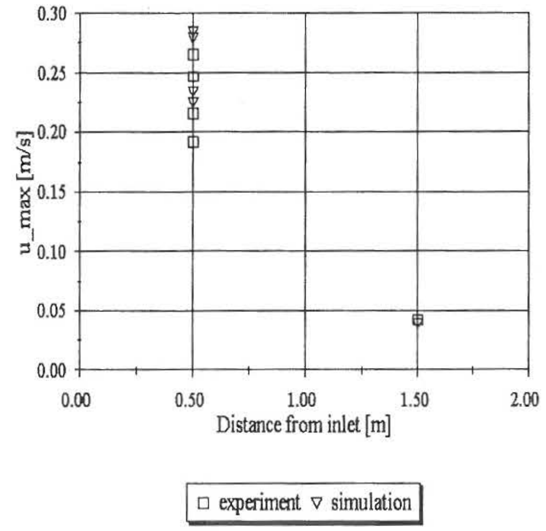


5.00 m from the end wall

Figure 2.61 *The average velocity profiles 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with the two radial jets with swirl. The diffusers are located 1.50 and 4.50 m from the left end wall.*

The velocity profiles through the room (figure 2.61) show good agreement at the ceiling but 4.00 and 5.00 m from the left end wall the simulated velocity is higher and lower, respectively than the measured velocity. This difference is caused by an inaccuracy in the measurements. This can be seen by comparing the measured velocity at the ceiling 4.00 and 5.00 m from the end wall with the measured velocity 2.00 and 1.00 m from the end wall, respectively. In the middle of the room and in the lower part of the room, the measured and the simulated velocity profiles are almost concordant. The largest difference between the two profiles is found 3.00 m from the left end wall. In the simulated room, the velocity is very close to 0.0 m/s whereas in the experimental room, the velocity is a little higher. This difference occurs because of the flow direction which is perpendicular to the overall flow direction in the room (see figure 2.31 page 27). In the measurements some of the velocity will be caught by the anemometer whereby the difference between the measurement and the simulation arises.

The flow in the upper part of the room is studied more closely by examining the velocity decay and the length scale. The maximum velocity, u_{max}, is shown as the absolute value. Values from both sides of the inlets are shown in the figure.



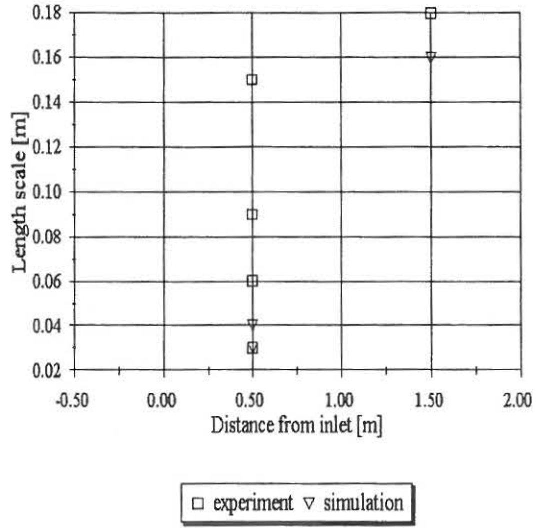


Figure 2.62 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The two radial jets with swirl are located 1.50 and 4.50 m from the left end wall.*

In figure 2.62 it is seen that the velocity decay in the simulated room is not completely concordant with the velocity decay in the experimental room. The maximum velocity at the ceiling is a little higher in the simulated room than in the physical room. Contrary to this, the length scale, δ, in the simulated room is considerably lower than in the experimental room. This could indicate that the simulated inlet with the halved air flow is not a satisfying construction of the physical inlet. This is investigated more closely by comparing the distance to the virtual origin and the individual constant of the diffuser in the two rooms.

The distance to the virtual origin, x_0, is found where the regression line in figure 2.62 to the right intersects with the x-axis. In the experimental empty room x_0 is found to 0.35 m and in the simulated room it is -0.35 m. This difference can be caused by the different initial inlet conditions in the two inlets so it does not necessarily mean that the simulated inlet must be changed. If the individual constant of the diffuser, K_{rs}, in the two rooms is identical, the construction of the simulated inlet is satisfying because also the overall flow and the velocity through the room are concordant with the experimental conditions. The individual constant of the diffuser, K_{rs}, is found from equation (2.3) (see section 2.1.3.5 page 31) and it is approximately 0.4 in both the physical and the simulated empty room. Hereby, the simulated inlet with a different initial flow than the physical inlet corresponds satisfyingly to the physical inlet.

The maximum velocity in the occupied zone is also of interest and in both the room with the 2-dimensional slot inlet and in the room with the 3-dimensional slot inlet it was found that the simulated maximum velocity is lower than the measured velocity. In the experimental room, the maximum velocity in the occupied zone is found to 0.015 m/s and the corresponding velocity in the simulated room is 0.012 m/s. Hereby, only a slight reduction of the velocity is found by it is probably because of the stagnant air since both velocities are close to 0.0 m/s.

2.2.3.2 The Room with Office Furniture

In the simulations of the physical set-up with normal office furniture, furniture volumes (the loss coefficient, f, equal to 0.5 m^{-1}) represent the physical furniture. Because the simulation is 3-

dimensional, the furniture volumes have the size and location of the physical furniture like it was the case with the 3-dimensional slot inlet (see section 2.2.2.2). The main purpose of the investigations is to find out if the furniture volume also can represent the normal office furniture in this case. The experimental set-up (see figure 2.32 page 27) is the same as in the room with the 3-dimensional slot inlet and by that the simulated set-up is identical. Figure 2.63 shows the simulated set-up.

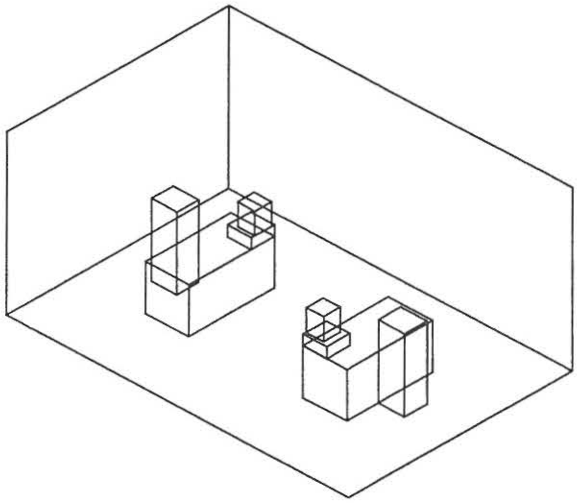
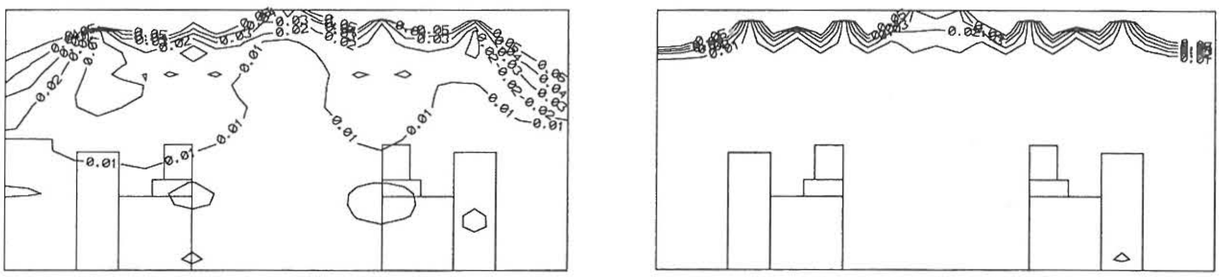


Figure 2.63 *The simulation of the physical set-up with office furniture.*

The investigations of the simulation with the furniture volume are concentrated on the velocity level, the velocity profiles, the velocity decay at the ceiling, the length scale, the distance to the virtual origin and the individual constant of the diffuser. At first, the velocity level in the experimental furnished room is compared with the simulated furnished room.

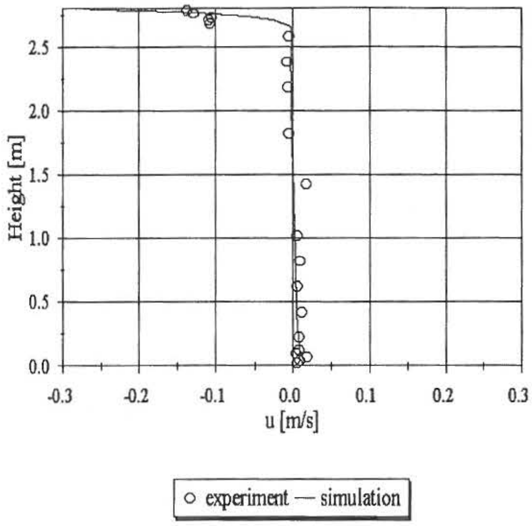


The experimental furnished room *The simulated furnished room*

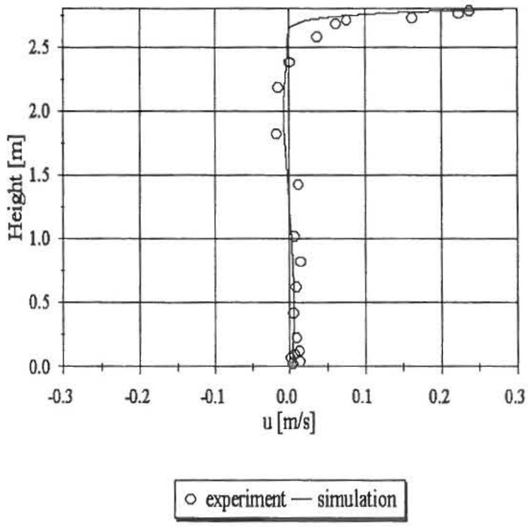
Figure 2.64 *The velocity level in the experimental and simulated furnished room.*

In the figure of the velocity level only the velocities lower than or equal to 0.05 m/s are shown. At the ceiling, the simulation is concordant with the experiment. In the lower part of the room, the same picture is found as in the comparison of the two empty rooms (see figure 2.60 page 58) where in the experimental room a velocity of 0.01 m/s is found whereas in the simulated room no velocity is visible. This was to be expected because it was found in the experiments that the furniture reduces the velocity level in the lower part of the room.

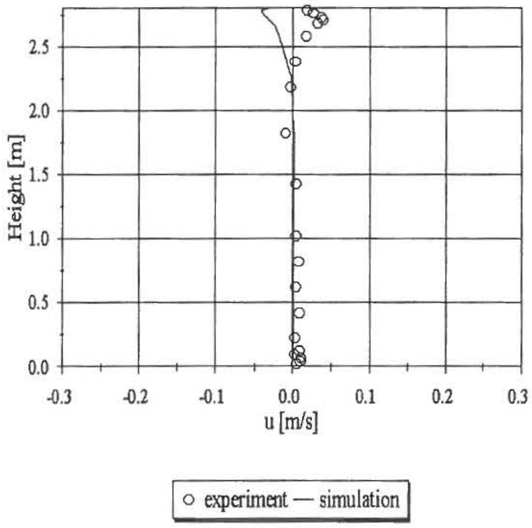
The simulation with the furniture volume is investigated further by comparing the velocity profiles through the room with the measured velocity profiles. The positive direction of the velocities is defined in figure 2.25 page 22.



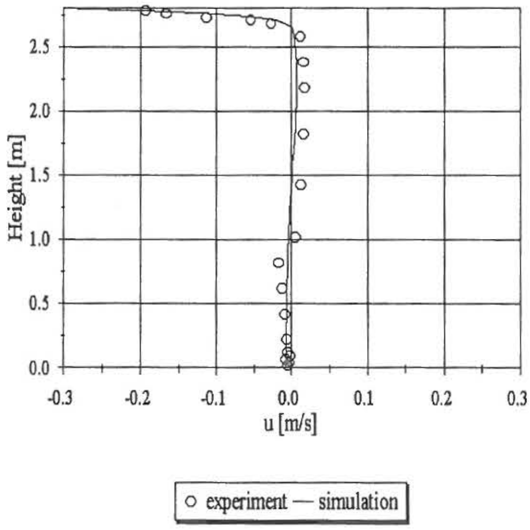
1.00 m from the end wall



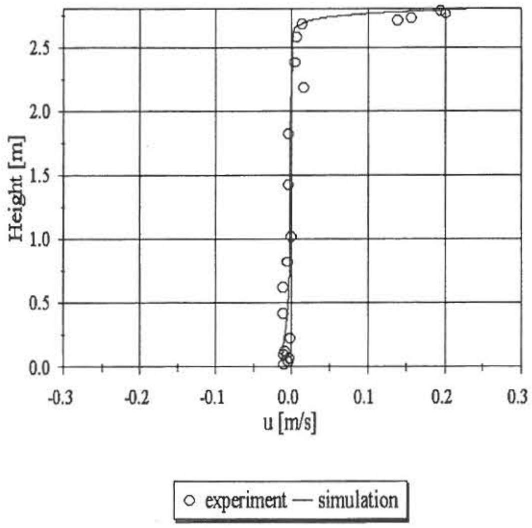
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



5.00 m from the end wall

Figure 2.65 *The average velocity profiles 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the furnished room with the two radial jets with swirl. The diffusers are located 1.50 and 4.50 m from the left end wall.*

The velocity profiles through the room show that at the ceiling, the simulated velocity is higher than the measured velocity. This is the opposite picture of what was found in the investigations of the simulated furnished room with the 3-dimensional slot inlet. In figure 2.65 it is found 3.00 m from the left end wall that the direction of the simulated velocity is opposite the measured velocity. In the lower part of the room, the velocity in the simulated furnished room is similar to the velocities measured in the experimental furnished room. This suggests that the furniture volume (f equal to 0.5 m^{-1}) is a suitable representation of the normal office furniture. However, the jet at the ceiling has to be investigated further because of the higher velocity in the simulated room. The investigations must also be done because of the difference in the construction of the physical and the simulated inlet.

The investigations of the jet at the ceiling are concerning the velocity decay, the length scale, the distance to the virtual origin and the individual constant of the diffuser. Figure 2.66 shows the velocity decay and the length scale in the experimental and the simulated furnished room. The maximum velocity, u_{max}, is shown as the absolute velocity. Values from both sides of the inlets are shown.

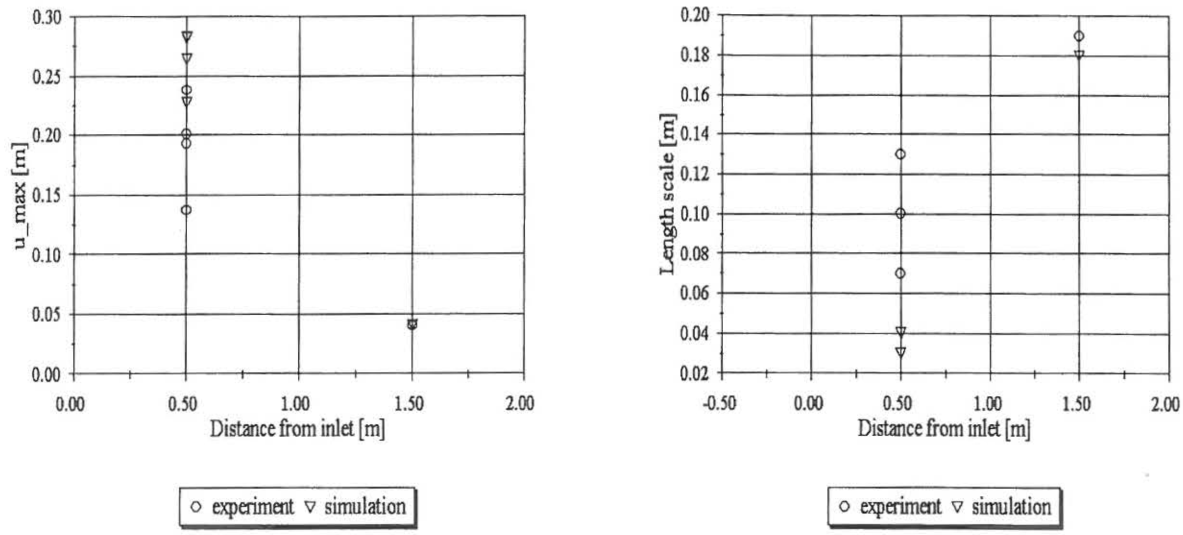


Figure 2.66 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The two radial jets with swirl are located 1.50 and 4.50 m from the left end wall.*

Figure 2.66 shows that the maximum velocity in the simulated furnished room is a little higher than in the experimental furnished room. Opposite to this, the length scale, δ, is lower in the simulated room than in the physical room. These results were also found in the comparison of the two corresponding empty rooms so it is probably the different construction of the simulated inlet that causes the differences in the velocity decay and the length scale.

Finally, the distance to the virtual origin, x_0, and the individual constant of the diffuser, K_{rs}, are examined to find out if the furniture volume is a good representation of the physical normal office furniture. In the comparison of the empty room it was found that x_0 was not identical in the experimental and the simulated room. This is also the case in the two furnished rooms where x_0 is 0.35 m and -0.35 m in the experimental and the simulated room, respectively. Thereby, the same x_0 is found in the empty room and the furnished room in both the experimental and the simulated room. The individual constant of the diffuser, K_{rs}, is also studied and it is found from the equation (2.3) (see section 2.1.3.5 page 31). In the simulated furnished room, K_{rs} is approximately 0.4 and this was also found in the experimental furnished room and in the two empty rooms. Hereby, it can be concluded that the furniture volume is suitable for the simulation of the normal office furniture in the room with the two radial jets with swirl.

The maximum velocity in the occupied zone is also an interesting parameter to investigate. It was found in the investigations made in the room with the 2-dimensional slot inlet and in the room with the 3-dimensioal slot inlet that furniture reduces the maximum velocity in the occupied zone. This was also found in the experiments with the two radial jets with swirl. Table 2.6 shows the maximum velocity in the occupied zone of the empty and of the furnished room and both the experiments and the simulations are shown.

	Experiment		Simulation	
	empty room	furnished room	empty room	furnished room
u_{rm} [m/s]	0.015	0.011	0.012	0.012
$u_{rm}/u_{rm,0}$		0.73		0.99

Table 2.6 *The maximum velocity in the occupied zone in the experiment and the simulation of the empty and the furnished room ($u_{rm,0}$ and u_{rm} respectively).*

In table 2.6 it is shown that in the simulation $u_{rm}/u_{rm,0}$ is equal to 0.99 in spite of that the velocity in both the empty and the furnished room is 0.012 m/s. This is because the velocities in the table are both rounded values. The table shows that the reduction of the maximum velocity in the simulated furnished room is insignificant. This can be caused by the almost stagnant air in the room. The table also shows that the reduction of velocity is larger in the experiment than in the simulation. This was also found in both the room with the 2-dimensional and the 3-dimensional slot inlet.

In the investigations made of the simulation with and without furniture it is found that a simulated quadrilateral inlet with half the air flow is a good representation of the physical circular inlet. It is also found that the furniture volume (f equal to 0.5 m^{-1}) is suitable for representing normal office furniture in the room with the two radial jets with swirl. Hereby, it is found from the isothermal investigations with the three types of inlets that the furniture volume is a good representation of normal office furniture in a mixing ventilated room. This result is independent of the set-up of the furniture and the furniture volume is valid in both 2- and 3-dimensional simulations.

The simulated reduction of the maximum velocity in the occupied zone is insignificant and this is different from the other simulated results and from the experimental results. This difference is possibly caused by the general air movements in the room with the two radial jets with swirl where the air in the occupied zone is almost stagnant.

The isothermal experiments and simulations with the three types of inlets are investigated more closely in the next section.

2.3 Results

The investigations of the isothermal experiments and simulations can include many topics. In this thesis is chosen to concentrate on how normal office furniture influences the jet under the ceiling and the velocity level in the occupied zone of the room where the maximum velocity in the occupied zone is of special interest. Furthermore, the momentum flow in the room is studied. Investigations have already been made in these fields by /16/, /22/ and /40/.

In the examination of the experiments and the corresponding simulations, the jet under the ceiling, the velocity level in the room and the maximum velocity in the occupied zone have already been studied. In the investigations made in this section, the experiments and simulations are extended with the further simulations made with the 2-dimensional slot inlet (see section 2.2.1.3). Hereby, the investigations also contain the effects of different height, length, location and number of furniture volumes.

2.3.1 The Jet under the Ceiling

It is important to find out if the jet under the ceiling is influenced by normal office furniture because the undisturbed jet is the base of the design procedures for ventilation systems when experiments and simulations are not used.

In the experiments and the corresponding simulations with the 2-dimensional slot inlet (see section 2.1.1 and 2.2.1) it was found that normal office furniture does not influence the jet under the ceiling. This was also found in the experiments with the 3-dimensional slot inlet and the two radial jets with swirl (see section 2.1.2 and 2.1.3) but in the simulation of the 3-dimensional slot inlet with the furniture volume representing the office furniture, the jet under the ceiling was slightly influenced. This disturbance of the jet does not necessarily mean that normal office furniture influences the jet under the ceiling because in the simulation of the two radial jets with swirl it was found that the furniture does not influence the jet under the ceiling. Hereby, it could be an unsuitable loss coefficient, f, used for the volume resistance that causes the disturbance of the jet so that the furniture volume (f equal to 0.5 m^{-1}) does not represent the office furniture in the simulation of the 3-dimensional slot inlet.

That affecting the jet under the ceiling is possible has already been found by /22/ and /40/. Both authors found that solid boxes can disturb the jet under the ceiling so that the velocity decay is increased and by that the individual constant of the diffuser is reduced. Furthermore, /40/ found that when the solid boxes reach a certain height, the average velocity level in the room increases.

In the following investigations it is studied how the individual constant of the diffuser is affected by normal office furniture in the further simulations with the 2-dimensional slot inlet (see section 2.2.1.3). The individual constant of the diffuser is used as reference value because if the individual constant is invariable, the velocity decay of the jet is constant and by that the jet is undisturbed.

The individual constant of the diffuser, K_p, is found from equation (2.2) page 16. The further simulations with the 2-dimensional slot inlet are described in section 2.2.1.3 and they are carried out in three different room lengths: 3.75, 5.40 and 7.50 m. The 5.40 m long room corresponds to the physical room. In all three cases, the individual constant of the diffuser, K_p, in the empty room is used as reference. Table 2.7 shows K_p for the three empty rooms.

	3.75 m	5.40 m	7.50 m
K_p	3.2	3.2	2.9

Table 2.7 *The individual constant of the diffuser, K_p, found in the empty rooms with the 2-dimensional slot inlet.*

In table 2.7 it is seen that K_p in the 7.50 m long room is smaller than in the other two rooms. The difference is caused by the length of the room since the inlet conditions are identical in the three rooms.

In the 3.75 m room all simulations made with the furniture volume have K_p equal to 3.2 and thereby no influence on the jet under the ceiling is found. This conclusion is valid for one and two furniture volumes and it shows that the size and location of the furniture volume is unimportant.

The experiments and the corresponding simulations in the 5.40 m room with the 2-dimensional slot inlet showed no influence from the furniture on the jet under the ceiling (see section 2.1.1 and 2.2.1). In the further simulations made in this room variations in height, length, location and the number of furniture volumes are tested (see section 2.2.1.3). It is found in the simulations with the furniture volume located in the half of the room opposite the inlet that in all the cases, except three, the furniture volume does not disturb the jet under the ceiling. The three exceptions are all with a 2.70 m furniture volume starting at the middle of the room (see figure 2.67).

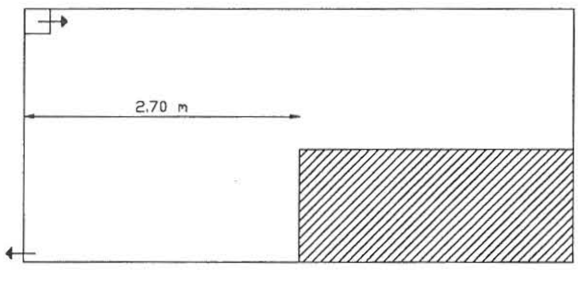


Figure 2.67 *The simulations of the 2.70 m furniture volume starting at the middle of the room.*

It is not all the used heights (0.50, 0.75, 1.10, 1.80 and 2.00 m) that cause a disturbance of the jet under the ceiling but only the three highest furniture volumes. In these three cases K_p is equal to 3.0 and this corresponds to a 6% reduction of K_p. The same reduction of K_p was also found in the simulation with a furniture volume covering the whole floor area (see figure 2.50 page 47). Opposite to this, the simulations with the furniture volume in the end of the room with the inlet show no disturbance of the jet and the simulation with the 3.42 m furniture volume located symmetrical about the middle of the room does not either. Hereby, it can be concluded that the location of the furniture volume is decisive for if the jet under the ceiling is influenced by the furniture. Disturbing the jet is most likely if the furniture is located in the area of maximum velocity in the occupied zone /7/, /27/, /28/ and /30/. Furthermore, the furniture volume has to be long to create a disturbance of the jet under the ceiling. For the small furniture volumes, the size and location does not seem to change the influence on the jet under the ceiling and either does the number of furniture volumes.

The simulations made with furniture volumes in the 7.50 m room have all the same K_p as the empty room. Hereby, the jet under the ceiling is not affected by the furniture no matter where it is located and its size or number.

From the investigations of the influence from normal office furniture on the jet under the ceiling it can be concluded that usually does normal office furniture not affect the jet. When the furniture volume gets sufficiently large, it reduces K_p and by that increase the velocity decay at the ceiling and specially if the furniture volume is located in the area of maximum velocity in the occupied zone. In the investigations made by /22/ and /40/ solid boxes were used instead of normal office furniture. The authors found that the boxes increased the velocity decay compared with the empty room. These results agree with the results found in this thesis because both authors have used a relatively large area for the boxes and they are located in the part of the room where the maximum velocity of the occupied zone is to be found. Furthermore, because solid boxes are used and not a porous volume, the air is forced to stay over the boxes. This means that the flow can be considered to take place in a room with a reduced height equal to the distance from the boxes to the ceiling. The simulations made in this thesis show that the velocity decay hereby is increased (see table 2.7). When the space requirements for offices /34/ are fulfilled it is seldom that a real office will contain a large furnished area. Hereby, it is assumed that in a normal office, the jet under the ceiling is not influenced by the furniture. This means that the design procedures for ventilation systems such as the flow element theory /7/, /27/, /28/ and /30/ that are based on the assumption that the room is empty can be used in an office under isothermal conditions.

2.3.2 The Velocity Level in the Occupied Zone

In the isothermal experiments and simulations of the furnished room it was found that the velocity level in the lower part of the room is reduced by the furniture. By that, the maximum velocity in the occupied zone is also reduced and the reduction is 25-35% in the experiments and 15-20% in the corresponding simulations. The difference in the reduction of the maximum velocity in the occupied zone is caused by the difference between the physical furniture and the furniture volume. The physical furniture forces the air to go around it whereas the furniture volume affects the air uniformly. The difference could also be caused by the coise of grid points, turbulence model etc. The largest difference in the simulated value and the measured value is found in the room with the 2-dimensional slot inlet. The reason for this is that in the experiments a completely 2-dimensional flow cannot be created because, e.g. the furniture is 3-dimensional whereas in the simulations the flow is 2-dimensional. Furthermore, the measurements are only made in the centre line of the experimental room.

Investigating how furniture influences the velocity level in the occupied zone is important because the velocity in the room must not cause discomfort. It was found by /16/, /22/ and /40/ that both office furniture and solid boxes reduce the velocity level in the room and by that the results found in the experiments and the corresponding simulations in this thesis are supported. It is now investigated if the further simulations with the 2-dimensional slot inlet (see section 2.2.1.3) also show this behaviour.

All the further simulations made with the 2-dimensional slot inlet show that the velocity level in the occupied zone is reduced by the furniture. Also in the three cases where the jet under the ceiling was influenced by the furniture (see section 2.3.1) the velocity level is reduced. Hereby, it can be concluded that normal office furniture under isothermal conditions reduces the velocity level in the occupied zone of a room.

When designing ventilation systems it is the maximum velocity of the occupied zone that is of interest because if it is equal to or lower than 0.15 m/s in an office, draught is avoided /1/, /5/, /8/, /9/, /17/, /41/ and /43/. In the light of this, a method for the determination of the maximum velocity in the occupied zone is developed. In the experiments and simulations carried out in this thesis several things regarding the furniture have been tried out: The same office furniture has been used in three different set-ups, the location of the furniture volume has been changed, in some situations five different heights have been tested and finally, one and two furniture volumes have been used. The set-ups have been made with three different inlet types and in four different room sizes where two of the rooms have only been simulated.

The maximum velocity in the occupied zone of the furnished room can be determined from many parameters. It has among other things been tested if the maximum velocity in the occupied zone of the furnished room, u_{rm}, is a function of the distance from the inlet to the beginning of the furniture volume (L'+H+a and b in figure 2.68), if u_{rm} is a function of the distance from the inlet to the middle of the furniture volume (L'+H+c and d in figure 2.68) and if u_{rm} is a function of the total length of the furniture volume in the main flow direction (x+y in figure 2.68).

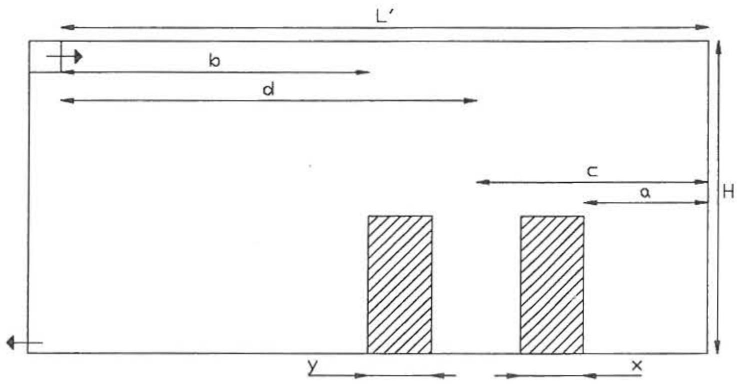


Figure 2.68 The distances tested in connection with the determination of the maximum velocity in the occupied zone of the furnished room.

When choosing the method for the determination of u_{rm} it is important that a common method valid for all situations tested in this thesis is found. This means that the method is not dependent on the type of inlet and on the size of the room. Since the allowable maximum velocity in the occupied zone of the empty room, $u_{rm,0}$, is known, it is chosen to determine u_{rm} in proportion to $u_{rm,0}$. By studying the results from the tests of the parameters connected to u_{rm} it is found that $u_{rm}/u_{rm,0}$ is a function of the total length of the furniture volume in the main flow direction, L_{fur} (x+y in figure 2.68). The total length of the furniture is a parameter that is simple to find and therefore the maximum velocity of the furnished room is easily found. Figure 2.69 shows $u_{rm}/u_{rm,0}$ as a function of L_{fur} and in the figure both the experimental and the simulated results are shown together with their regression line.

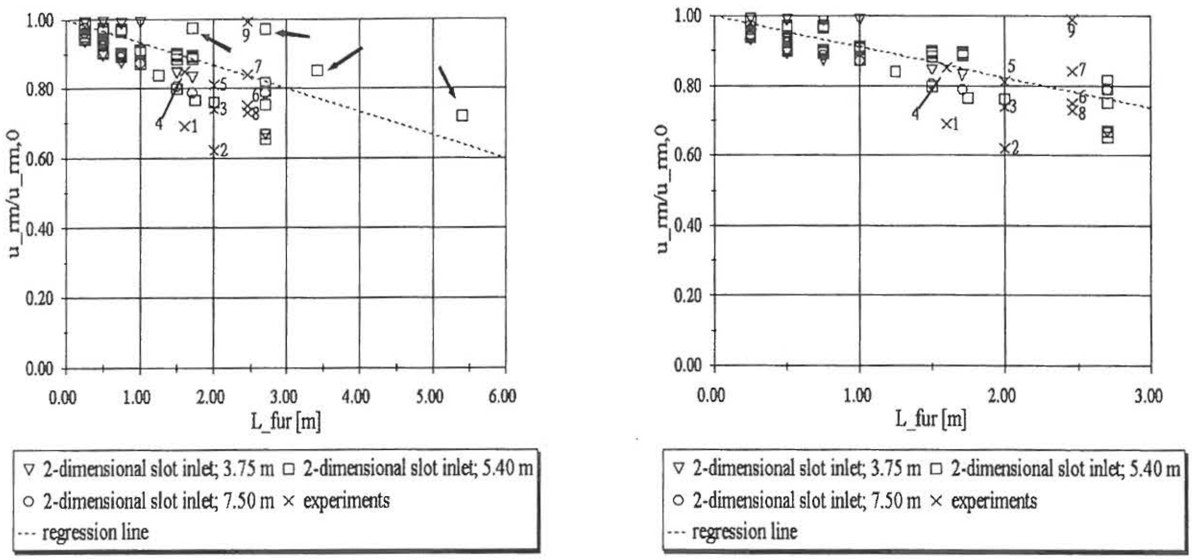


Figure 2.69 *The non-dimensional maximum velocity in the occupied zone as a function of the total length of the furniture volume in the main flow direction. In the figure ×1-×3 correspond to the experimental set-up 1-3 in the room with the 2-dimensional slot inlet and ×4 and ×5 correspond to the simulations of set-up 1-3. The 3-dimensional slot inlet is represented by ×6 and ×7 corresponding to the experiment and the simulation, respectively. The two radial jets with swirl are represented by ×8 and ×9 corresponding to the experiment and the simulation, respectively.*

In figure 2.69 to the left all experimental and simulated results are shown. It can be seen that four values are outside the main area (see the arrows in the figure). They represent the simulations with the 2-dimensional slot inlet where the furniture volume is located in the half of the room where the inlet is and where the furniture volume is located in both halves of the room (see figure 2.50 page 47). The four values show a smaller reduction of the maximum velocity in the occupied zone of the furnished room than the other simulations. This means that when the furniture volume is located outside the area of maximum velocity or that it covers most of the floor area it only disturbs the flow in the lower part of the room insignificantly. The four values are excluded from figure 2.69 to the right. The regression line in figure 2.69 to the right has the equation:

$$\frac{u_{rm}}{u_{rm,0}} = 1 - C \cdot L_{fur} \tag{2.6}$$

where
u_{rm} : Maximum velocity in the occupied zone in the furnished room [m/s].
$u_{rm,0}$: Maximum velocity in the occupied zone in the empty room [m/s].
C : A constant of 0.088 m^{-1}.
L_{fur} : Total length of the furniture volume in the main flow direction [m].

This equation is only valid for room lengths between 3.75 and 7.50 m and it must be taken with reservations because the simulated and measured values are distributed around the regression line. It can also in figure 2.69 to the right be seen that some of the non-dimensional velocities are close to 1. This is especially the case in the 3.75 m long room where the phenomenon with the furniture volume being present in both halves of the room also occurs. Furthermore, the equation is not valid for furniture volumes covering most of the floor or furniture volumes only present outside the area of the maximum velocity in the occupied zone. In these cases the reduction of the maximum velocity in the furnished room is smaller than the one calculated by equation 2.6.

Figure 2.69 shows that the experimental values are lower than the corresponding simulated values. This is caused by the difference in the physical furniture and the furniture volume where the physical furniture forces the air to go around it whereas the furniture volume affects the air flow uniformly.

As a parallel to figure 2.69 and equation (2.6), the non-dimensional maximum velocity in the occupied zone is shown as a function of L_{fur}/L where L is the total length of the room. This is done to test a non-dimensional version of equation (2.6).

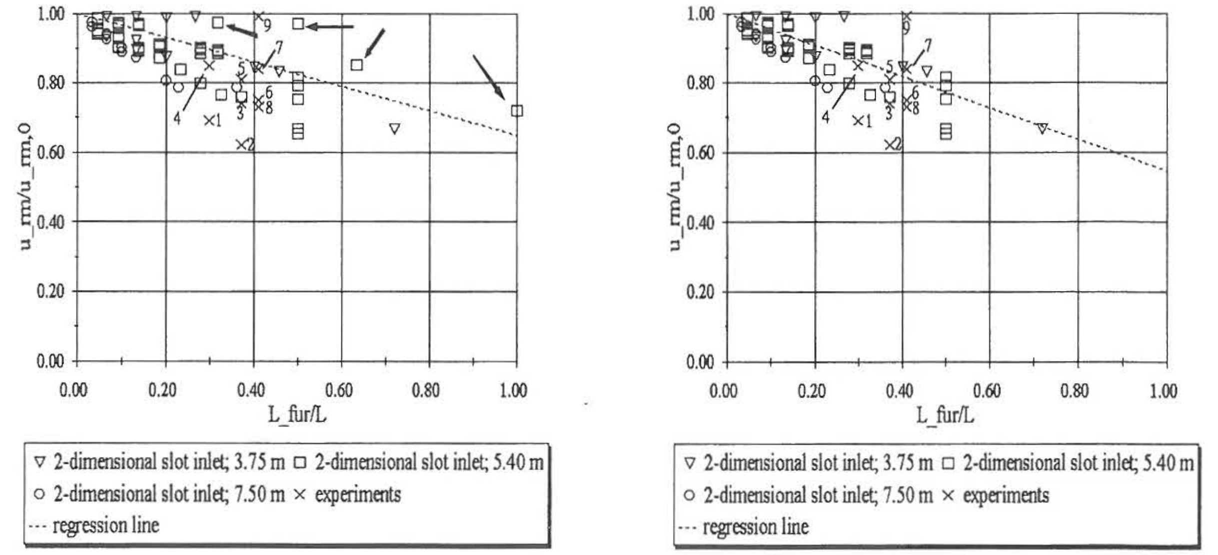


Figure 2.70 *The non-dimensional maximum velocity in the occupied zone as a function of the non-dimensional total length of the furniture volume in the main flow direction. In the figure ×1-×3 correspond to the experimental set-up 1-3 in the room with the 2-dimensional slot inlet and ×4 and ×5 correspond to the simulations of set-up 1-3. The 3-dimensional slot inlet is represented by ×6 and ×7 corresponding to the experiment and the simulation, respectively. The two radial jets with swirl are represented by ×8 and ×9 corresponding to the experiment and the simulation, respectively.*

By studying figure 2.70 to the left it is seen that the four values from before (see the arrows in the figure) still are outside the main area and they are on that basis excluded from figure 2.70 to the right. It is also seen in the figure that the results do not get less scattering in this way of presentation. The equation for the regression line is:

$$\frac{u_{rm}}{u_{rm,0}} = 1 - C \cdot \frac{L_{fur}}{L} \qquad \textbf{(2.7)}$$

where
- u_{rm} : Maximum velocity in the occupied zone in the furnished room [m/s].
- $u_{rm,0}$: Maximum velocity in the occupied zone in the empty room [m/s].
- C : A constant of 0.452.
- L_{fur} : Total length of the furniture volume in the main flow direction [m].
- L : Length of the room [m].

This equation must be taken with the same reservations as equation 2.6.

In the investigations of the influence from normal office furniture on the velocity level in the occupied zone it was found that the furniture reduces the velocity level and by that the maximum velocity in the occupied zone. This has also been found by /16/, /22/ and /40/ and it is valid for both solid boxes and normal office furniture. In the investigations it was also found that the maximum velocity in the occupied zone of the furnished room is dependent on the total length of the furniture in the main flow direction where increasing furniture length decreases the maximum velocity in the occupied zone of the furnished room. However, if the furniture is only located outside the area of maximum velocity of if it covers most of the floor, the reduction is not very large and in some situations, the maximum velocity in the furnished room is almost identical to the maximum velocity in the empty room.

2.3.3 The Momentum Flow through the Room

The momentum flow in a room has been investigated by many researchers and there has been some discussion about whether the momentum flux in the flow direction is constant, increasing or decreasing. Traditionally, it was assumed by, e.g. /36/ that the momentum flux in any jet is very nearly constant. Contrary to this /19/ showed that this is not true for a plane free jet. He found that the momentum flux is reduced appreciably because the induced flow towards the jet has a component in the direction opposite to the main flow jet and because of the pressure field generated in the ambient fluid. These results are supported by /18/, /20/, /37/ and /38/ and furthermore, /20/ found that the angle at which the induced flow streamlines enter the jet, is the basic parameter that determines whether the jet momentum flux increases, remains constant or decreases.

In this thesis it is investigated how normal office furniture influences the momentum flow through the room. An investigation of the momentum flow through the empty room is not made because it is found more interesting to concentrate on the effects of the furniture. Some investigations in the field of obstacles in the occupied zone have already been made by /22/ who found that solid boxes reduce the momentum flow in the entire room. In the integration of the momentum flow only velocities in the flow direction are used. The momentum flow is only found at the ceiling and at the floor. The momentum flow is determined by /36/:

$$I = \rho \int u^2 dA \qquad \textbf{(2.8)}$$

where
- I : The momentum flow [N].
- ρ : The air density; 1.19 kg/m^3.
- u : Velocity [m/s].
- A : Area [m^2].

Equation (2.8) is used in connection with the velocity profile and to determine the momentum flow at the ceiling the area and velocities of upper part of the profile are used. The momentum flow at the floor is determined from the area and the velocities found from the lower part of the velocity profile. The following figure 2.72 shows the momentum flow in the three rooms with the 2-dimensional slot inlet and figure 2.74 and 2.75 show the momentum flow through the room with the 3-dimensional slot inlet and the two radial jets with swirl, respectively.

In figure 2.72 the momentum flow, I, is made non-dimensional with the initial momentum flow, I_0, which is 0.143 N in all three cases. The non-dimensional momentum flow is shown as a function of the distance from the inlet, x', made non-dimensional with the distance from the inlet to the opposite wall, L' (see figure 2.71).

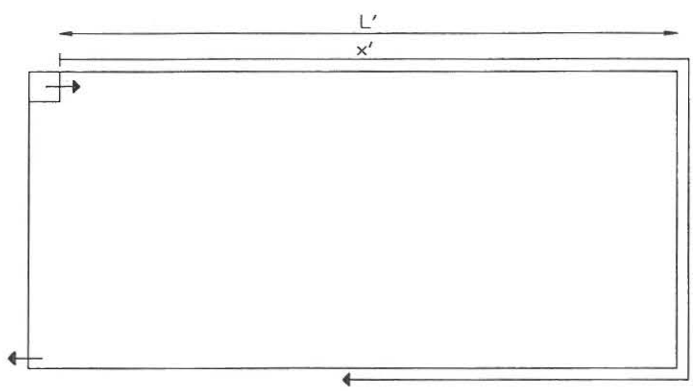
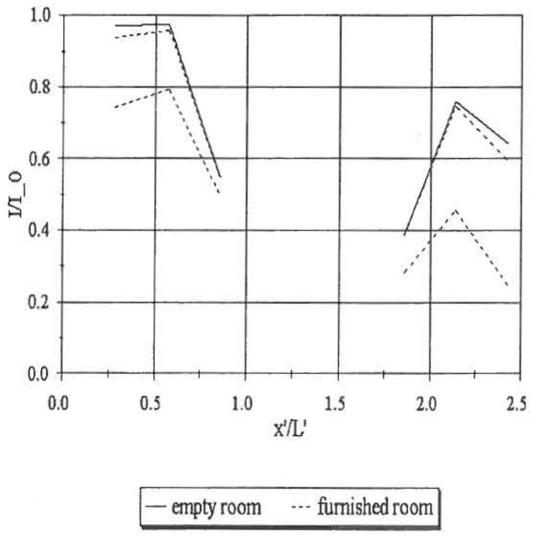
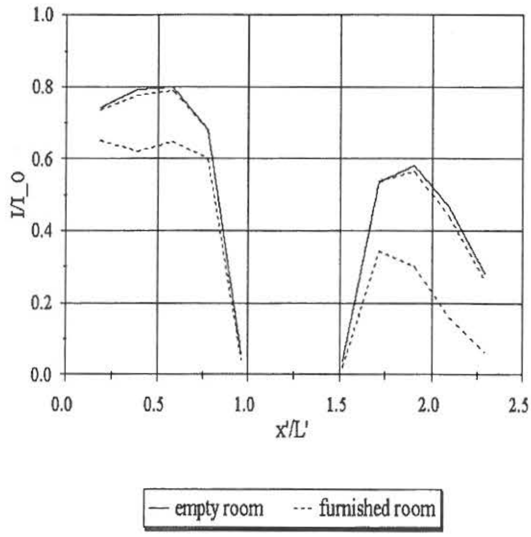


Figure 2.71 *The distance from the inlet, x', and the distance from the inlet to the opposite wall, L'.*

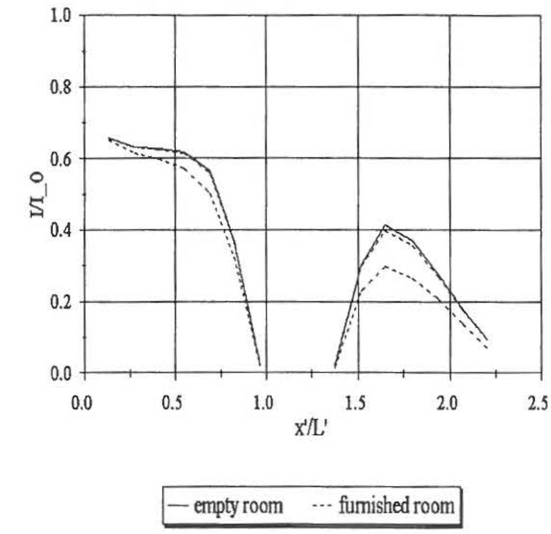
In the figure of the momentum flow through the room only the simulated results are shown and the simulations of the furnished rooms are not shown individually. Instead the maximum and the minimum values are shown (the dotted lines in the figure). This means that the simulated results are to be found between the two dotted lines.



3.75 m room



5.40 m room



7.50 m room

Figure 2.72 The momentum flow through the three rooms with the 2-dimensional slot inlet.

In figure 2.72 it is found in all three cases that the normal office furniture reduces the momentum flow both at the ceiling and at the floor. It is also seen that the pattern of the momentum flow through the furnished room is identical with the momentum flow through the empty room. Figure 2.72 also shows that the momentum flow is higher at the ceiling than at the floor. This is different from the results found by /33/ who found that the momentum flow in the jet and in the reverse flow is identical.

In the 3.75 m room it is seen that some set-ups with furniture only reduce the momentum flow close to the inlet (x'/L' lower than 0.6 and higher than 2.2) whereas in some cases the momentum flow in the entire room is reduced.

In the 5.40 m room the same pattern is found as in the 3.75 m room. The overall level of momentum is lower in the 5.40 m room than in the 3.75 m room and the reason is the different length of the two rooms. It is also seen that the reduction of momentum flow caused by the furniture is smaller in the 5.40 m room than in the 3.75 m room.

In the 7.50 m room the momentum flow through the room shows the same behaviour as in the 3.75 and 5.40 m room. The only difference is that in this situation the momentum flow close to the inlet is only slightly influenced by the furniture whereas in the other two rooms this location showed the largest reduction. This difference is probably caused by the size of the furniture which is much smaller compared to the total size of the room in the 7.50 m room than in the 3.75 m room.

It is now investigated if the normal office furniture used in the room with the 3-dimensional slot inlet also reduces the momentum flow through the room. In figure 2.74 the momentum flow, I, is made non-dimensional with the initial momentum flow, I_0, which is 0.160 N. The non-dimensional momentum flow is shown as a function of the distance from the left end wall, x'', made non-dimensional with the length of the room, L (see figure 2.73).

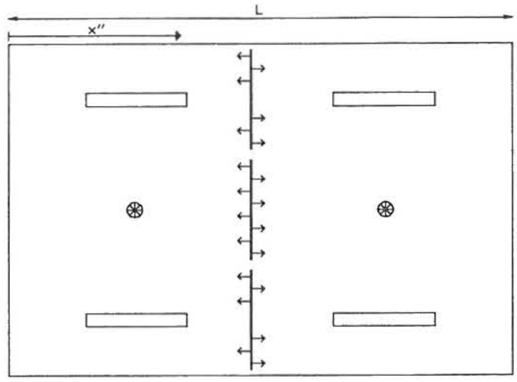


Figure 2.73 *The distance from the left end wall, x'', and the length of the room, L. Both the 3-dimensional slot inlet and the two radial jets with swirl are shown in the figure.*

In figure 2.74 which shows the momentum flow through the room with the 3-dimensional slot inlet, only the simulated empty and furnished room are shown. The 3-dimensional slot inlet is located 2.90 m from the left end wall which corresponds to 0.48 and 1.98 on the x-axis in the figure.

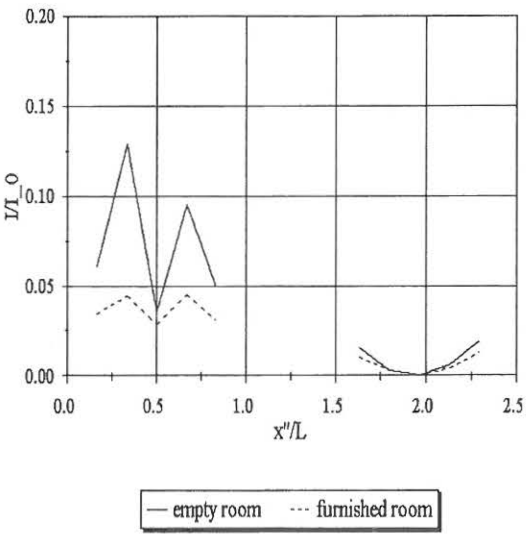


Figure 2.74 *The momentum flow through the room with the 3-dimensional slot inlet. The diffuser is located at x''/L equal to 0.48 and 1.98.*

The figure shows that at the ceiling in the empty room the momentum flow is not identical at the two sides of the inlet. This could be caused by the fact that the inlet is not located in the middle of the room whereby the distance from the inlet to the end wall influences the momentum flow. This behaviour is not as clearly at the floor and in the furnished room. In the room with the 3-dimensional slot inlet the momentum flow in the entire room is also influenced by the furniture. In this room the smallest reduction of the momentum flow is found close to the inlet. At the ceiling, the largest reduction is found where the furniture is located (2.00 and 4.00 m from the left end wall corresponding to 0.33 and 0.66 on the x-axis) whereas at the floor, the largest reduction is close to the walls. This could be caused by the lower K_p-value in the furnished room (see section 2.2.2 page 56). In the room with the 3-dimensional slot inlet it is also found that the momentum flow in the reverse flow is smaller than the momentum in the jet and hereby, the same tendency is found as in the room with the 2-dimensional slot inlet.

The momentum flow through the room with the two radial jets with swirl is now investigated to see if the same conclusions can be made with this type of inlet. In figure 2.75 the momentum flow, I, is made non-dimensional with the initial momentum flow, I_0, which is 0.089 N. The non-dimensional momentum flow is shown as a function of the distance from the left end wall, x'', made non-dimensional with the length of the room, L (see figure 2.73). Also here only the simulated results are shown. The two radial jets with swirl are located 1.50 and 4.50 m from the left end wall and this corresponds to 0.25 and 13.3 together with 0.75 and 10.3 on the x-axis in the figure.

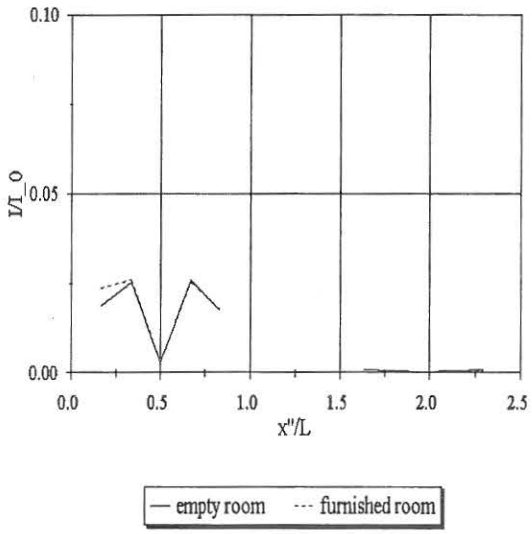


Figure 2.75 *The momentum flow through the room with the two radial jets with swirl. The two diffusers are located at x''/L equal to 0.25 and 13.3 and x''/L equal to 0.75 and 10.3.*

In the room with the two radial jets with swirl it is very difficult to see any influence from the furniture on the momentum flow through the room. Because of the construction of the inlet the jet loses much momentum at the beginning and therefore, the momentum found in the rest of the room is almost equal to 0.

In the investigations made of the influence from normal office furniture on the momentum flow through the room it was found (when excluding the room with the two radial jets with swirl because of the almost stagnant air in the room) that the furniture reduces the momentum flow both at the ceiling and at the floor. This reduction is caused by a deformation of the velocity profile and a decreasing velocity level in the room. The studies show that the size of the furniture compared to the size of the room is determined for how big the reduction of the momentum flow is so that when the size of the room increases the reduction decreases. It is also found that the momentum flow in the jet at the ceiling is larger than the momentum flow at the floor.

3 The Thermal Case

This chapter contains a description of the thermal experiments with normal office furniture and the corresponding 3-dimensional simulations. The experiments and the simulations are carried out in both the room with the 3-dimensional slot inlet and in the room with the two radial jets with swirl. In both cases the principle of ventilation is mixing ventilation. In both rooms one set-up with furniture is made and this set-up is simulated with the CFD program Flovent.

3.1 Experiments

The thermal experiments are only made in one of the rooms used in the isothermal experiments and it is physically situated in Aachen, Germany. In this room two types of inlets are used: the 3-dimensional slot inlet and the two radial jets with swirl. Only one set-up with normal office furniture and a thermal load is tested in both rooms. In the following the thermal set-up is described and a comparison with the corresponding empty room is made. The comparison is concerning the overall velocity level in the room, the velocity profiles through the room, the velocity decay at the ceiling, the length scale, the distance to the virtual origin, the individual constant of the diffuser and the maximum velocity in the occupied zone.

3.1.1 Experiment with the 3-dimensional Slot Inlet

The room with the 3-dimensional slot inlet used in the thermal experiment is identical to the room with the 3-dimensional slot inlet used in the isothermal experiment (see section 2.1.2). The inlet and the exhausts are described in section 2.1.2 page 17 and 18.

3.1.1.1 Measuring Equipment

In the thermal experiment velocities and temperatures are measured. The velocities are measured at the same locations and in the same heights as in the isothermal experiment (see figure 2.18 page 18 and figure 2.19 page 19).

The temperature is measured in the inlet and in the exhaust together with the temperature gradient two places in the room. The inlet temperature is approximately 6.0 K colder than the exhaust temperature.

3.1.1.2 Experimental Set-up with Office Furniture and a Thermal Load

In the thermal experiment with normal office furniture the same set-up is used as in the isothermal experiment (see section 2.1.2.3 page 19 and 20 and figure 3.1).

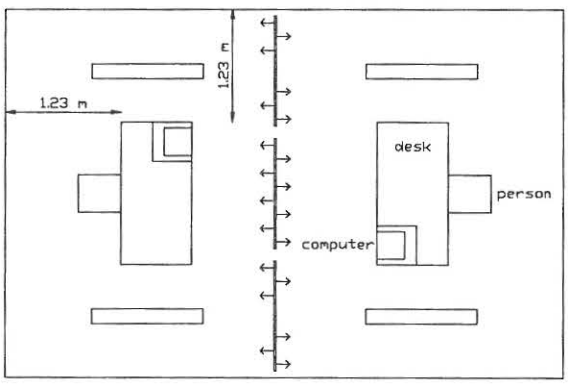


Figure 3.1 The set-up with office furniture with a thermal load.

The thermal load in the room is 600 W. It is distributed so that 100 W is present in each person, in each computer and in each monitor. This means that in figure 3.1 the indication "computer" covers 200 W because the monitor is on top of the computer.

3.1.1.3 The Flow in the Room with Office Furniture and a Thermal Load

The air movements in the room are studied by adding smoke to the room air. The measured velocities are presented in section 3.1.1.4 together with the velocities measured in the empty room.

In the room with the slot inlet, the air moves along the ceiling in both directions to the end wall like it is the case in the empty room. At the end wall the jet deflects down along the wall but only a very little part of the air reaches the floor. Instead the air moves into the middle of the room on its way down to the floor. The amount of air reaching the floor is smaller in the furnished room with a thermal load than in the empty room. This difference is caused by the heat sources which force the air directly over them upwards. Figure 3.2 shows the air movements in the room with office furniture and a thermal load of 600 W. The flow in the empty room is described in section 2.1.2.2.

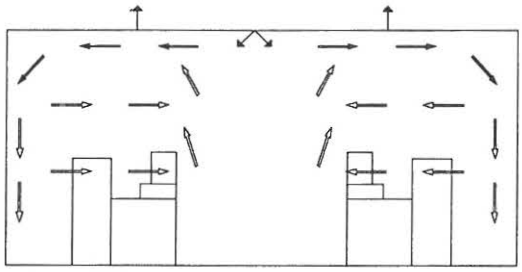
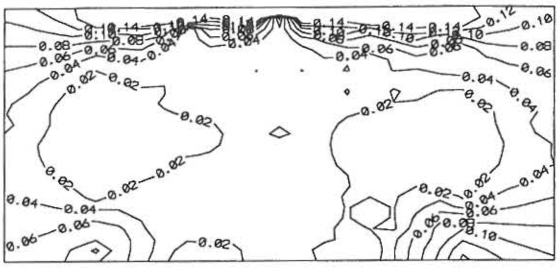


Figure 3.2 The air movements in the furnished room with a thermal load.

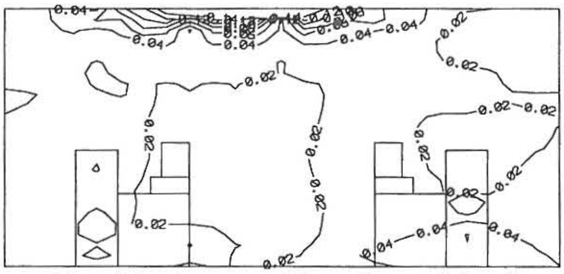
3.1.1.4 Differences Between the Empty and the Furnished Room

In the isothermal experiments and simulations it was found that the normal office furniture does not affect the jet under the ceiling whereas the velocity in the lower part of the room is reduced. The thermal experiment with normal office furniture in the room with the 3-dimensional slot inlet is investigated similar as in the isothermal case. The velocity level in the room is studied at first.

By using the average value of the measured velocity across the room (see figure 2.18 page 18) the velocity level in the room is found by interpolating with the method Kriging (see footnote 1 page 10). Like in the case with the isothermal investigations, the wall velocity of 0.0 m/s is not used in the interpolation because the distance from the end wall to the point of measurement is to big to get a realistic representation of the results. The following figure shows the measurements made in the empty and the furnished room with the 3-dimensional slot inlet.



Empty room

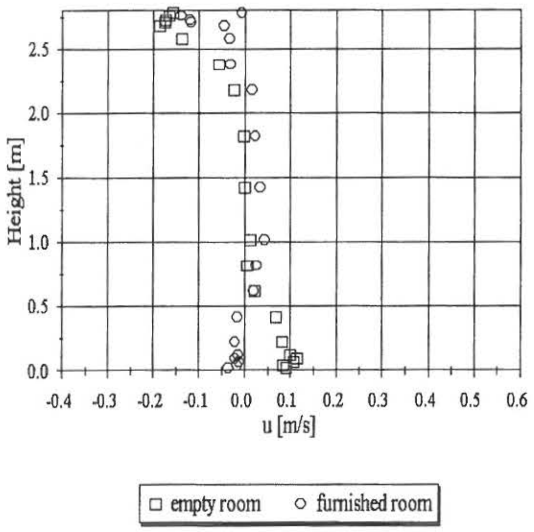


Furnished room with a thermal load

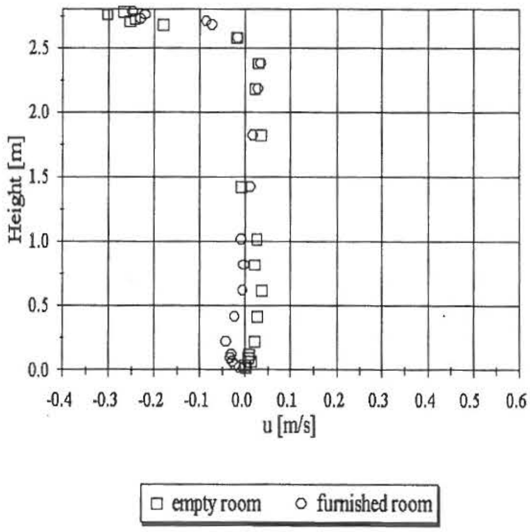
Figure 3.3 *The velocity level in the empty room and in the furnished thermal room with the 3-dimensional slot inlet.*

In figure 3.3 only velocities lower or equal to 0.14 m/s are shown. At the ceiling, the comparison between the empty room and the furnished room with a thermal load shows that the velocity in the furnished room is lower than in the empty room. Hereby, it is indicated that the furniture with a thermal load has an influence on the jet under the ceiling. In the middle of the room no particular difference seems to occur between the two rooms. In the floor area some difference occurs especially in the corners of the room where the velocity is decreased by the furniture with a thermal load. Hereby, the same pattern in the occupied zone is found as in the isothermal case. At the ceiling the two cases show opposite results because the jet is unaffected by the furniture in the isothermal case.

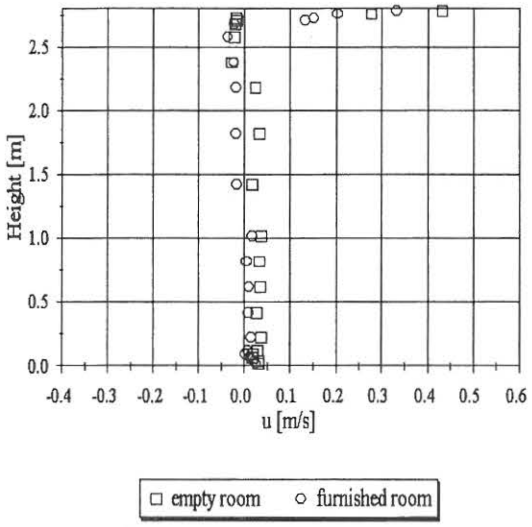
The results found in the study of the velocity level are investigated more closely by examining the velocity profiles through the room. By drawing the velocity profiles the average value of the velocity across the room is used like it was the case by drawing the velocity level in the room. The positive direction of the velocities is defined in figure 2.25 page 22.



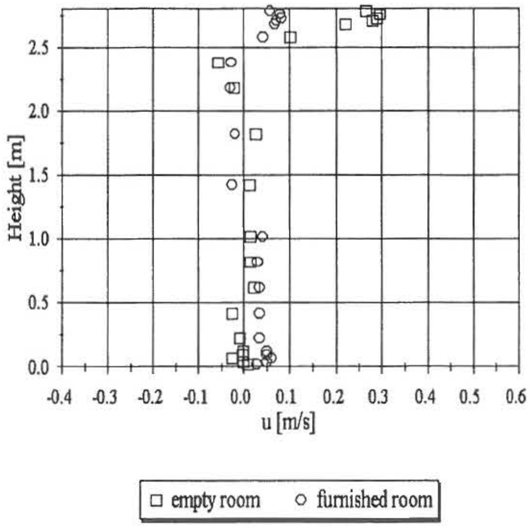
1.00 m from the end wall



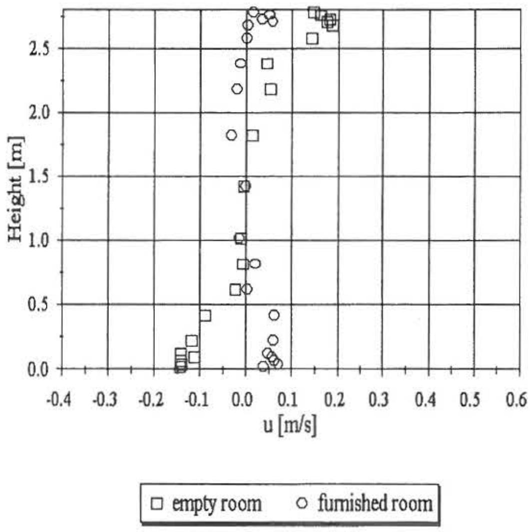
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall

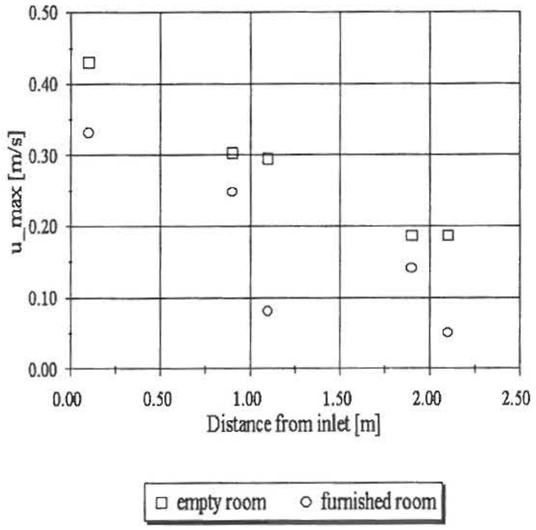


5.00 m from the end wall

Figure 3.4 *The average velocity profiles measured 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with the 3-dimensional slot inlet. The slot inlet is located 2.90 m from the left end wall.*

The velocity profiles through the room show that at the ceiling, the velocity in the furnished room with a thermal load is lower than in the empty room. This could indicate that the individual constant of the diffuser is reduced in the furnished room compared with the empty room. In the middle of the room, the two velocity profiles are similar. At the floor, the direction of the velocities is changed except close to the inlet (3.00 m from the left end wall). This is caused by the heat sources that affect the four other measuring points because the furniture with a thermal load is located between them (see figure 3.1 page 79). The heat sources create an upwards directed flow and to make this flow the air from the floor area is drawn towards the heat sources.

To study the jet under the ceiling more closely the velocity decay and the length scale are examined. In figure 3.5 the two values are shown and in connection with the velocity decay the absolute velocity, u_{max}, is drawn. The length scale is determined as the distance from the ceiling to $u_{max}/2$ /7/ and /30/ (see equation (2.1) page 15). The figure shows values from both sides of the inlet.



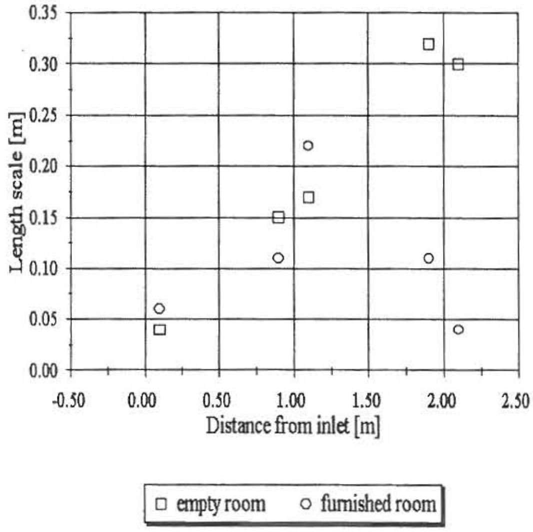


Figure 3.5 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The 3-dimensional slot inlet is located 2.90 m from the left end wall.*

In figure 3.5 it is seen that the maximum velocity at the ceiling in the furnished room with a thermal load is considerable lower than in the empty room. This was also shown in the study of both the velocity level and the velocity profiles through the room. Hereby, the furniture with a thermal load influences the jet under the ceiling. This must be caused by the upwards moving air over the heat sources because in the isothermal case with the same set-up of furniture no effect on the jet under the ceiling was found. The study of the length scale shows that close to the inlet the two situations are similar. Farthest away from the inlet (1.90 and 2.10 m from the inlet) the length scale in the furnished room is considerably lower than in the empty room. This means that the jet under the ceiling is influenced by the heat sources so that the jet is pressed together by the upwards directed flow over the heat sources. How large an influence the furniture with a thermal load has on the flow in the upper part of the room is investigated closer by comparing the distance to the virtual origin and the individual constant of the diffuser in the furnished room with the values found in the empty room.

The distance to the virtual origin, x_0, is found from figure 3.5 to the right where the regression line intersects the x-axis. x_0 is found to 0.35 m if only the three first values are included. This x_0 was also found in the empty room but as described earlier the jet under the ceiling is influenced by the furniture. The individual constant of the diffuser, K_p, is found from equation (2.2) (see page 16) and it is found to 0.6 which is only half of the value found in the empty room (K_p equal to 1.3). Some of this reduction is caused by the thermal conditions rather than by the furniture because /32/ have found a reduction of the individual constant of the diffuser in a thermal room without furniture. Hereby, it can be concluded that the furniture with a thermal load does influence the jet under the ceiling so that the velocity is reduced. This is different from the isothermal case where the jet was unaffected.

That an influence on the jet occurs is expected because a thermal load will affect the air movements in a room /7/, /27/, /28/ and /30/. The Archimedes number, Ar, is here an important parameter and Ar is determined by /30/ and represents the balance between the bouancy forces and the inertial forces in the flow:

$$Ar = \frac{g\beta l \Delta T_0}{u_0^2} \tag{3.1}$$

where
- g : Gravitational acceleration [m/s^2].
- β : Volume expansion coefficient; $3.419 \cdot 10^{-3}$ K^{-1}.
- l : Characteristic length [m]; equal to h in case of the slot inlet and equal to $(a_0)^{0.5}$ in case of the two radial jets with swirl.
- ΔT_0 : Temperature difference between the exhaust and the inlet [K].
- u_0 : Inlet velocity [m/s].

In the room with the 3-dimensional slot inlet Ar is found to $2.27 \cdot 10^{-4}$. Since the inlet air does not separate from the ceiling and continue into the occupied zone, the flow at the ceiling is not strongly influenced by the thermal forces.

To see how the air movements in the lower part of the room are affected by the furniture with a thermal load, the maximum velocity in the occupied zone is studied. In the isothermal case it was found that the furniture reduces the velocity level in the lower part of the room and by that the maximum velocity in the occupied zone. Table 3.1 shows the maximum velocity in the furnished room with a thermal load and in the empty room.

	empty room	furnished room
u_{rm} [m/s]	0.142	0.071
$u_{rm}/u_{rm,0}$		0.50

Table 3.1 *The maximum velocity in the occupied zone found in the empty and the furnished thermal room. The velocity in the furnished room, u_{rm}, is compared with the one found in the empty room, $u_{rm,0}$.*

The table shows that the maximum velocity in the occupied zone decreases when furniture with a heat load is present in the room which also was found from the study of the velocity level in the room (see figure 3.3 page 81). This was not to be expected on the basis of the investigations made by /27/ and /30/ where an increase of the velocity was found. The reduction of the maximum velocity in the occupied zone in the furnished room with a thermal load is larger than the one found in the isothermal case (see table 2.2 page 25) where the reduction was only 25%. The larger reduction of the maximum velocity in the occupied zone could be caused by the heat sources preventing the air from reaching the floor. Another reason is that the velocity of the jet at the ceiling is reduced and by that the air movements in the whole room are affected.

The experiment in the room with the two radial jets with swirl is now investigated to see if also here the jet under the ceiling is affected by the furniture with a thermal load and if the maximum velocity in the occupied zone is decreased compared with the empty room.

3.1.2 Experiment with the Two Radial Jets with Swirl

In the thermal experiment with the two radial jets with swirl, a room identical to the room in the isothermal experiment with two radial jets with swirl is used (see section 2.1.3). The inlet and exhaust conditions are described in section 2.1.3 page 25 and 26.

3.1.2.1 Measuring Equipment

Both velocities and temperatures are measured in the experiment in the room with the two radial jets with swirl. The velocities are measured at the same locations and in the same heights as in the isothermal experiment (see figure 2.29 and figure 2.30 page 26).

The temperature is measured in the inlet and in the exhaust together with the temperature gradient two places in the room. The exhaust temperature is approximately 6.0 K higher than the inlet temperature.

3.1.2.2 Experimental Set-up with Office Furniture and a Thermal Load

In the room with two radial jets with swirl the same set-up with office furniture is used as in the room with the 3-dimensional slot inlet. The set-up was also used in the isothermal experiment with this type of inlet. Section 2.1.2.3 describes the furniture and the set-up and the latter is also shown in figure 3.6.

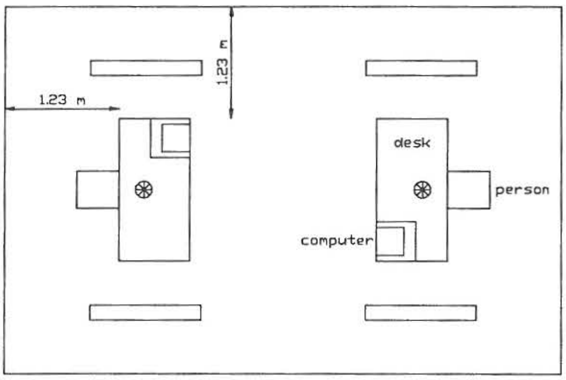


Figure 3.6 The set-up with office furniture with a thermal load.

The thermal load in the room is 600 W. It is distributed so that 100 W is present in each person, in each computer and in each monitor. This means that in figure 3.6 the indication "computer" covers 200 W because the monitor is on top of the computer.

3.1.2.3 The Flow in the Room with Office Furniture and a Thermal Load

The air movements in the furnished room with a thermal load are studied visually by adding smoke to the inlet air. The velocities measured in the room are presented in section 3.1.2.4 where they are compared with the measurements made in the empty room.

In the room with the two radial jets with swirl, the air from the two diffusers meets in the middle of the room and here a common jet moves down towards the floor. At the sides of the room, the air moves along the ceiling to the end wall. These flows were also found in the empty room. At the end wall the air is deflected downwards and most of the air moves to the middle of the room instead of reaching the floor. Where the heat sources are present, the air moves upwards. Figure 3.7 shows the air flow in the room with the two radial jets with swirl when office furniture and heat load is present in the room. The flow in the empty room with the two radial jets with swirl is described in section 2.1.3.4.

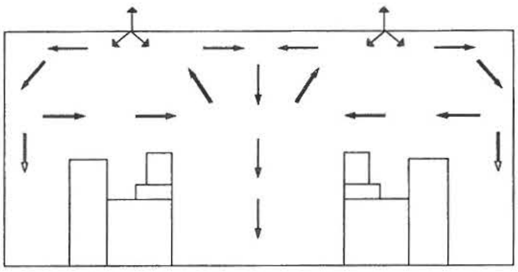
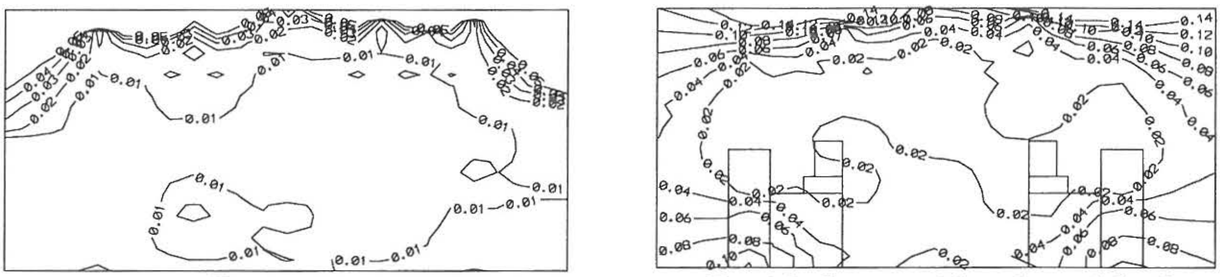


Figure 3.7 The air movements in the furnished room with a thermal load.

3.1.2.4 Differences Between the Empty and the Furnished Room

In the investigations of the thermal experiment in the room with the 3-dimensional slot inlet (see section 3.1.1) it was found that when furniture with a thermal load is present in the room, the velocity level at the ceiling is reduced and the maximum velocity in the occupied zone is also reduced. In the thermal room with the two radial jets with swirl similar investigations are carried out.

By using the average value of the measured velocity across the room (see figure 2.29 page 26) the velocity level in the room is found by interpolating with the method Kriging (see footnote 1 page 10). Like in the other isothermal and thermal cases, the wall velocity of 0.0 m/s is not used in the interpolation because the distance from the end wall to the point of measurement is to big to get a realistic representation of the results. The following figure shows the measurements in the empty and the furnished room with two radial jets with swirl.

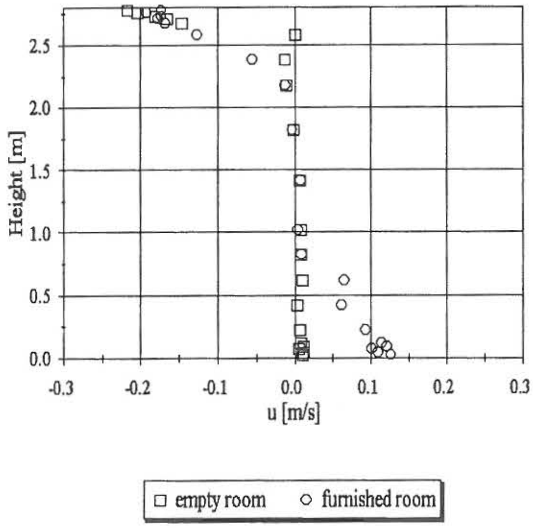


Empty room *Furnished room with a thermal load*

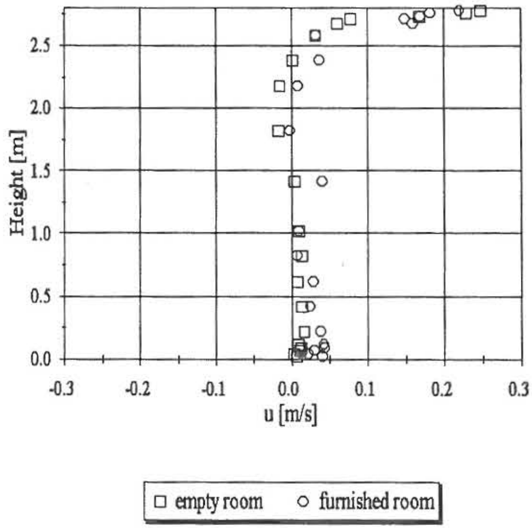
Figure 3.8 The velocity level in the empty room and in the furnished thermal room with two radial jets with swirl.

In the empty room (figure 3.8 to the left) only velocities lower than or equal to 0.05 m/s are shown whereas in the furnished room with a thermal load (figure 3.8 to the right) velocities lower than or equal to 0.14 m/s are shown. Hereby, it is clearly that the velocity level in the furnished room is increased compared with the empty room because showing the air movements in the empty room was not possible if the large scale going to 0.14 m/s was used. In figure 3.8 is found that at the ceiling, the velocity level in the two rooms is similar. This is different from the results found in the experiment with the 3-dimensional slot inlet where the velocity at the ceiling is reduced by the furniture with a heat load. In the lower part of the room, the velocity level in the furnished room is increased considerably from almost stagnant air movements to velocities up to 0.10 m/s. That the velocity level in the occupied zone is increased is the opposite of what was found in the thermal experiment with the 3-dimensional slot inlet.

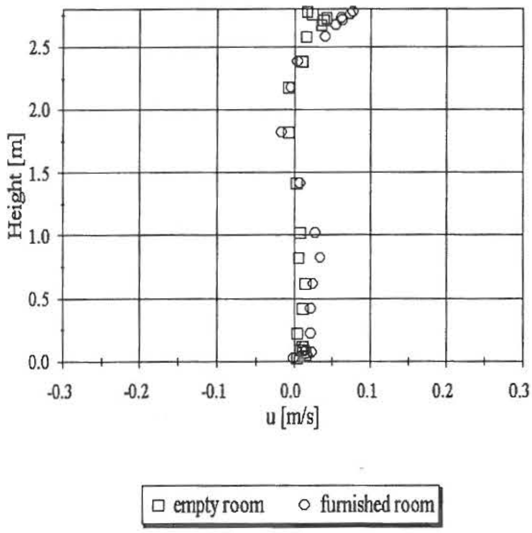
The velocity profiles through the room are compared to study the flow more closely. The direction of the velocities is defined in figure 2.25 page 22.



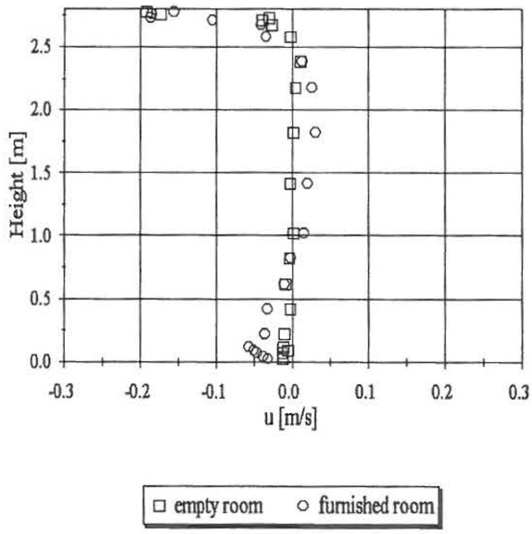
1.00 m from the end wall



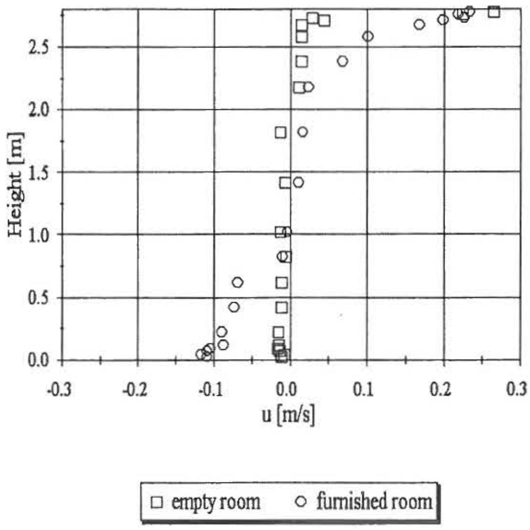
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall

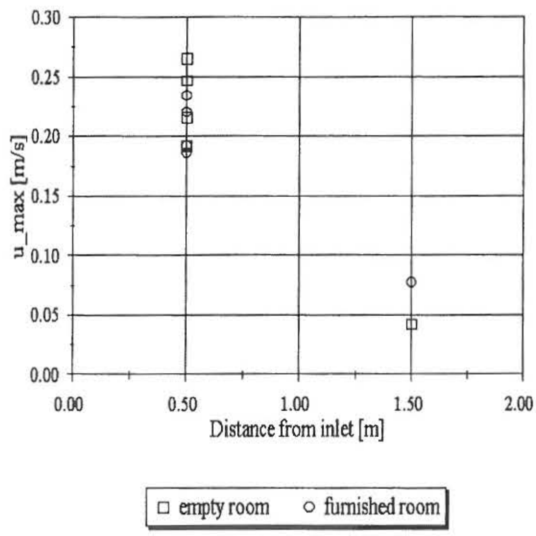


5.00 m from the end wall

Figure 3.9 *The average velocity profiles measured 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with two radial jets with swirl. The diffusers are located 1.50 and 4.50 m from the left end wall.*

By studying the velocity profiles through the room it is seen that at the ceiling, the velocity in the furnished room is a little lower than in the empty room except 3.00 m from the left end wall where the velocity is the furnished room is higher than in the empty room. The velocity profiles in the upper part of the room also show that the jet in the furnished room is a little wider than in the empty room. This will be studied more closely in the examination of the length scale. In the middle of the room the two profiles are similar. In the floor area, a large difference occurs between the furnished and the empty room. This was to be expected on the basis of /27/ and /30/.

The jet under the ceiling must be examined more closely to see how large an influence the small reduction in velocity found at the ceiling has. The investigations are concerning the velocity decay, the length scale, the distance to the virtual origin and the individual constant of the diffuser. Figure 3.10 shows the velocity decay and the length scale. In the drawing of the velocity decay, the absolute maximum velocity, u_{max}, is used and the length scale is defined as the distance from the ceiling to $u_{max}/2$ /7/ and /30/ (see equation (2.1) page 16). The figure shows values from both sides of the inlets.



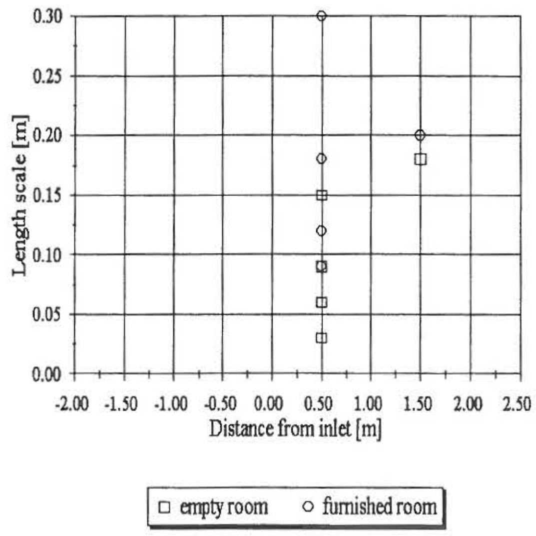


Figure 3.10 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The two radial jets with swirl are located 1.50 and 4.50 m from the left end wall.*

The velocity decay shows that the maximum velocity at the ceiling is slightly reduced in the furnished room which also was to be expected. The reduction is not as big as the one found in the room with the 3-dimensional slot inlet (see figure 3.5 page 83). This means that the reduction does not necessarily affect the individual constant of the diffuser, K_{rs}. By studying the length scale it is found that the length scale is higher in the furnished room with a heat load than in the empty room. This is not necessarily caused by the furniture but more likely by the thermal load because /32/ found that the jet broadens when a thermal load is in the room. The result found here was also indicated in the examination of the velocity profiles through the room.

The influence from the furniture with a thermal load is evaluated by comparing the distance to the virtual origin, x_0, and the individual constant of the diffuser, K_{rs}, in the furnished room with the values found in the empty room. In the furnished room with a thermal load x_0 is 1.75 m whereas it is only 0.35 m in the empty room. This means that the jet is wider in the furnished room than in the empty room which may come from both the thermal load and from the furniture. K_{rs} is found from equation (2.3) (see page 31) and it is equal to 0.4 in both the furnished and the empty room. Hereby, no particular influence on the jet under the ceiling is found which is the opposite of what was found in the thermal experiment with the 3-dimensional slot inlet. Because the jet under the ceiling is only slightly influenced, the increase in the width of the jet is probably caused by the thermal conditions rather than by the furniture. The Archimedes number is found from equation (3.1) page 84 and it is $2.60 \cdot 10^{-3}$.

The study of the maximum velocity in the occupied zone in the room with the 3-dimensional slot inlet showed that the furniture with a thermal load decreases the velocity compared with the empty room. In table 3.2 the maximum velocity in the occupied zone of the furnished room with the two radial jets with swirl is shown. In the table the value found in the empty room is also shown.

	empty room	furnished room
u_{rm} [m/s]	0.015	0.127
$u_{rm}/u_{rm,0}$		8.47

Table 3.2 *The maximum velocity in the occupied zone found in the empty and the furnished thermal room. The velocity in the furnished room, u_{rm}, is compared with the one found in the empty room, $u_{rm,0}$.*

The table shows that the maximum velocity in the occupied zone of the furnished room with a thermal load is considerably increased compared with the empty room. That the velocity increases was also expected /27/ and /30/ and it is the opposite of what was found in the investigations in the room with the 3-dimensional slot inlet and this in spite of that the heat load is identical in the two rooms. The difference occurs because in the empty room with the two radial jets with swirl the air is almost stagnant. The heat sources then create an upwards moving air flow and by that the air movements in the whole room are affected.

In the investigations of the thermal experiments it was found that normal office furniture with a thermal load affects the air movements in the room differently than normal office furniture without a thermal load. In the isothermal case the jet under the ceiling is not influenced by the furniture whereas the furniture with a heat load affects the jet under the ceiling. This disturbance of the jet can affect both the individual constant of the diffuser and the width of the jet (the distance to the virtual origin). Some of the reduction of the individual constant of the diffuser and the influence on the width of the jet is caused by the thermal conditions rather than by the normal office furniture. The individual constant of the diffuser decreases whereas the width of the jet increases. In the isothermal investigations it was found that the maximum velocity in the occupied zone is reduced by the furniture. This was also found in the thermal experiment in the room with the 3-dimensional slot inlet whereas in the thermal experiment in the room with the two radial jets with swirl the opposite is found. Here the maximum velocity in the occupied zone is increased considerably because the air movements in the empty room are almost stagnant and by that the thermal forces have a large effect.

In the next section the thermal simulations corresponding to the thermal experiments with normal office furniture with a heat load are described.

3.2 CFD Simulations

The thermal 3-dimensional simulations are only concerning the two experiments described in section 3.1. In the simulations the furniture volume (the loss coefficient, f, equal to 0.5 m^{-1}) is representing the normal office furniture like in the isothermal case. In the simulations the furniture volume has the same size as the physical furniture. To simulate the thermal load, a volume source with a fixed heat load is used. The size of the volume source is identical to the furniture volume. This means that, e.g. the volume source in a sitting dummy is located at the same place as the furniture volume of the dummy and it has the exact same size.

The purpose of these investigations is to find out if the furniture volume together with the volume source can create the same air movements in the room as was found in the experiments.

3.2.1 Simulation with the 3-dimensional Slot Inlet

In the simulation of the furnished room with the 3-dimensional slot inlet it is important that first the air flow in the simulated empty room is concordant with the air flow in the experimental room. This has already been done in section 2.2.2.1.

3.2.1.1 The Room with Office Furniture and a Thermal Load

The 3-dimensional simulation of the set-up with normal office furniture (see figure 3.1 page 79) is identical to the isothermal simulation of the same set-up (see section 2.2.2.2 page 52). Figure 3.11 shows the set-up used in the simulation with the furniture volumes and the volume sources.

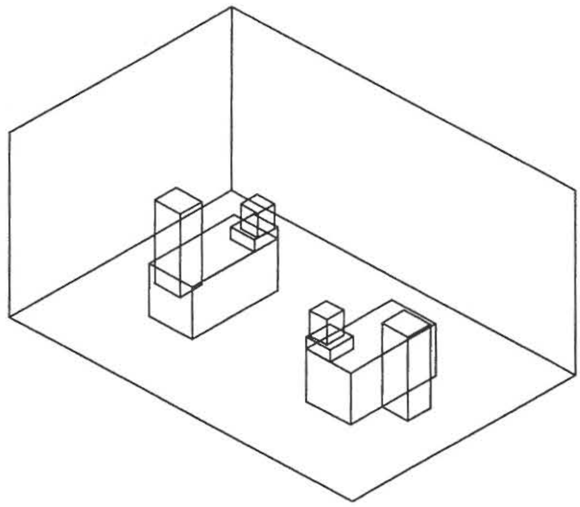
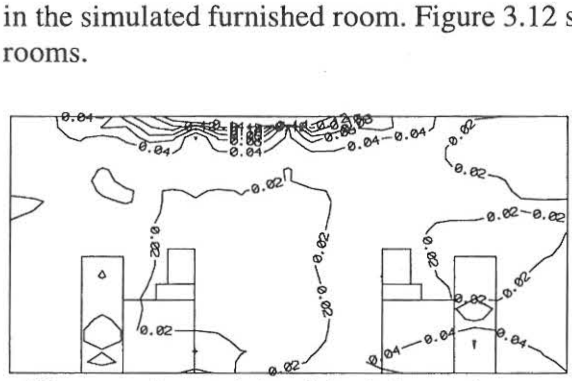


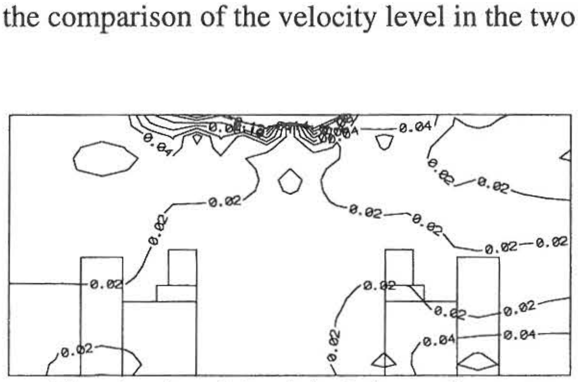
Figure 3.11 The simulation of the physical set-up with office furniture with a thermal load.

The volume sources are not visible in figure 3.11 because they have the same size as the furniture volumes. The heat load in the experiment is 100 W per unit but in the simulation a heat load of 60 W per unit is used. This is done so that the Archimedes number, Ar, (see equation (3.1) page 84) is identical in the two cases. The heat load is also reduced in the simulation because only the convection part of the heat load is used in the simulation. When 60 W per unit (equal to a total convective heat load of 360 W) is used, the temperature difference between the exhaust and the inlet is 5.7 K which is satisfying because the temperature difference in the experiment was approximately 6.0 K. In the simulation the Archimedes number is $2.16 \cdot 10^{-4}$ whereas it was found to $2.27 \cdot 10^{-4}$ in the experiment. This deviation is acceptable.

The investigations are concerning a comparison of the velocity level, the velocity profiles, the velocity decay, the length scale, the distance to the virtual origin, the individual constant of the diffuser and the maximum velocity in the occupied zone in the experimental furnished room and in the simulated furnished room. Figure 3.12 shows the comparison of the velocity level in the two rooms.



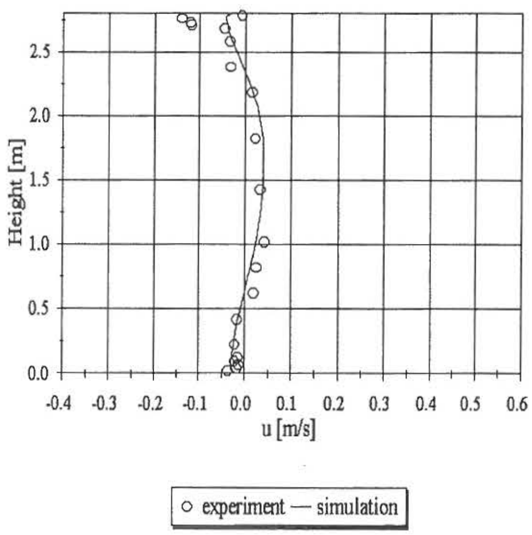
The experimental furnished thermal room



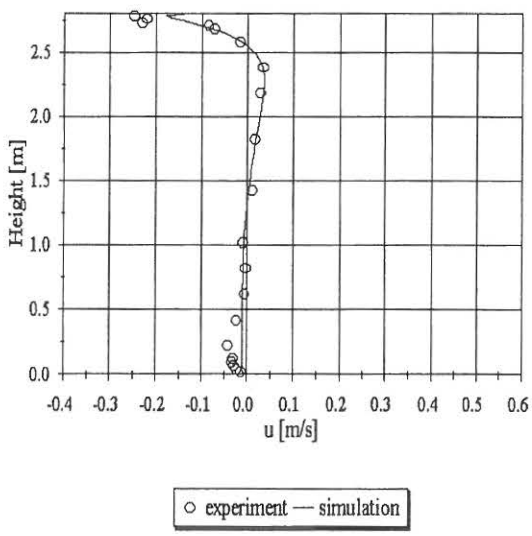
The simulated furnished thermal room

Figure 3.12 The velocity level in the experimental and simulated furnished room with a thermal load.

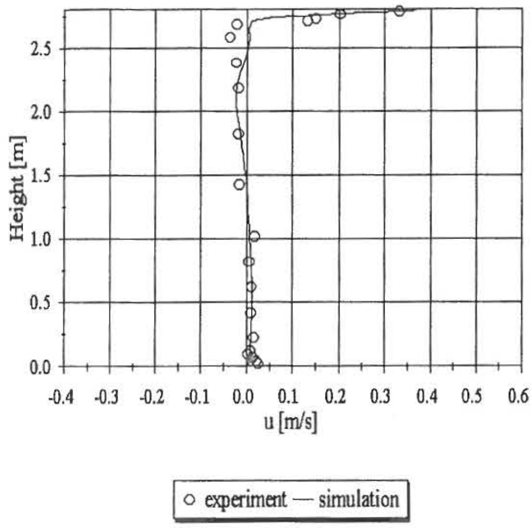
The comparison of the velocity level in the simulated room and the experimental room shows good agreement. In both cases the velocity in the lower right corner is higher than in the opposite corner. This means that the simulation with the furniture volumes and the volume sources representing normal office furniture with a thermal load is satisfying. The simulation is investigated further by studying the velocity profiles through the room together with the velocity profiles in the physical room. The positive direction of the velocities is defined in figure 2.25 page 22.



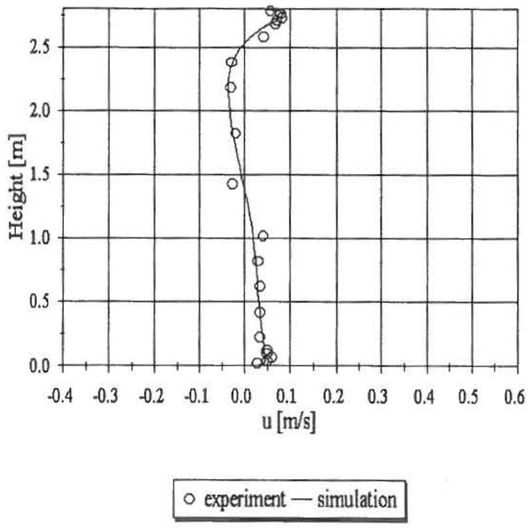
1.00 m from the end wall



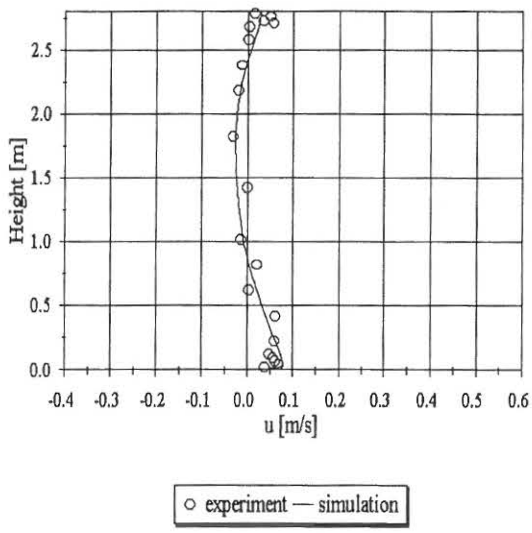
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



5.00 m from the end wall

Figure 3.13 *The average velocity profiles measured 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the room with the 3-dimensional slot inlet. The slot inlet is located 2.90 m from the left end wall.*

The study of the velocity profiles through the room shows that the velocity at the ceiling in the simulated room is lower than the measured velocity. This is probably caused by the furniture volume and not by the generation of the heat sources because the same tendency was found in the isothermal case (see figure 2.57 page 55). In the lower part of the room the simulated velocity profiles are similar the measured velocity profiles. On the basis of these investigations it is found acceptable to use the furniture volumes together with the volume sources.

As indicated in the study of the velocity profiles through the room some difference between the measured and the simulated velocity at the ceiling occurs. The effect of this is examined more closely by studying the velocity decay at the ceiling and the length scale. The maximum velocity at the ceiling, u_{max}, is shows as the absolute value in figure 3.14. Values from both sides of the inlet is shown in the figure.

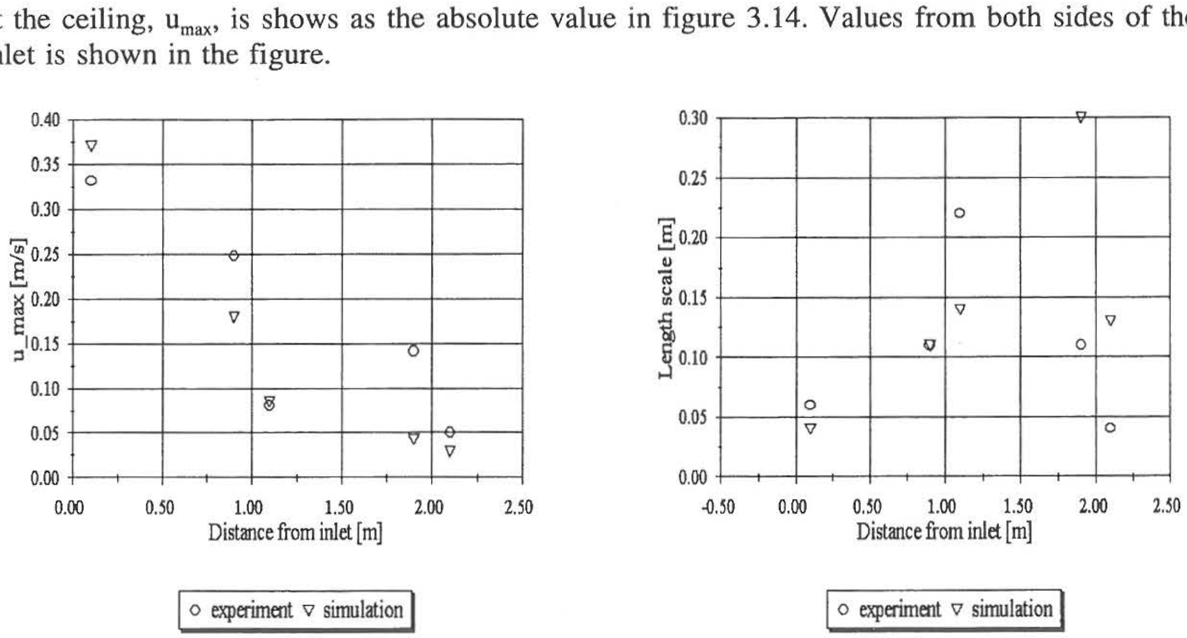


Figure 3.14 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The 3-dimensional slot inlet is located 2.90 m from the left end wall.*

Figure 3.14 shows that the velocity decay in the simulated furnished room with a heat load is not identical to the velocity decay in the physical room. Mostly, the measured velocity is higher than the simulated one. This is probably caused by the furniture volume as mentioned earlier because the comparison of the velocity decay in the isothermal case (see figure 2.58 page 56) shows the same picture. The study of the length scale shows that close to the inlet the value in the two cases is similar whereas farthest from the inlet (1.90 and 2.10 m from the inlet) the simulated length scale is higher than the measured value. Hereby, the simulated jet is not as affected by the heat sources as the experimental jet. To study the effects on the jet under the ceiling further, the distance to the virtual origin and the individual constant of the diffuser are investigated.

The distance to the virtual origin, x_0, is found where the regression line in figure 3.14 to the right intersects with the x-axis. In the simulated furnished room with a thermal load, x_0 is found to 0.35 m when the point farthest from the inlet is excluded. This is the same value as was found in the experimental furnished room with a thermal load. The individual constant of the diffuser, K_p, is found from equation (2.2) page 16 and in the simulated room it is found to 0.5 which is lower than in the experimental room (0.6). The difference in K_p is most likely caused by the furniture volume and not by the volume source because in the isothermal case, K_p in the simulation was also 0.1 lower than the measured value. This means that the furniture volume together with the volume source is an acceptable representation of the normal office furniture with a thermal load.

The maximum velocity in the occupied zone is also an important parameter to examine. From the study of the velocity level in the room (see figure 3.12 page 92) it was found that the velocity in the lower part of the room is similar in the two cases. Table 3.3 shows the maximum velocity in the occupied zone in the experimental and simulated furnished room. The velocity is compared with the velocity in the empty room.

	Experiment		Simulation	
	empty room	furnished room	empty room	furnished room
u_{rm} [m/s]	0.142	0.071	0.069	0.078
$u_{rm}/u_{rm,0}$		0.50		1.13

Table 3.3 *The maximum velocity in the occupied zone found in the empty and the furnished room with a thermal load. The velocity in the furnished room, u_{rm}, is compared with the one found in the empty room, $u_{rm,0}$.*

The table shows that in the simulated room the maximum velocity in the occupied zone is increased compared with the empty room whereas in the experiment it is decreased. The increase in velocity is very small compared with the increase found in the room with the two radial jets with swirl (see table 3.2 page 90). The different results could arise from the generation of the heat source where only the convective part is represented. Hereby, the flow over the heat sources is not so strong in the simulation as in the experiment. By that more of the flow reaches the floor and by this the maximum velocity in the occupied zone is increased in the simulated room compared with the experimental room.

The investigations of the thermal simulation of the furnished room have shown that the simulation is similar in the ceiling area whereas opposite results are found in the occupied zone. Since the results found in the occupied zone of the simulated room are similar to other investigations /27/ and /30/ it is found that the furniture volume together with the volume source represents the normal office furniture with a thermal load satisfyingly.

In the next section the simulation of the furnished room with the two radial jets with swirl is investigated to see if the furniture volume together with the volume source also is suitable in this case.

3.2.2 Simulation with the Two Radial Jets with Swirl

Before the 3-dimensional simulation of the room with a thermal load is made the flow in the empty rooms must be concordant. The description of the simulated empty room is made in section 2.2.3.1.

3.2.2.1 The Room with Office Furniture and a Thermal Load

The experimental set-up of normal office furniture with a thermal load is simulated 3-dimensionally using the furniture volume and the volume source in the same way as in the case with the 3-dimensional slot inlet (see section 3.2.1.1). Figure 3.15 shows the simulated set-up of' furniture with a thermal load (see figure 3.6 page 85 for the experimental set-up).

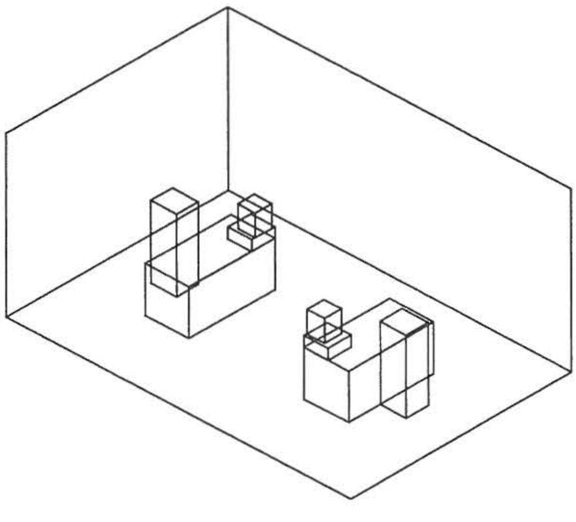
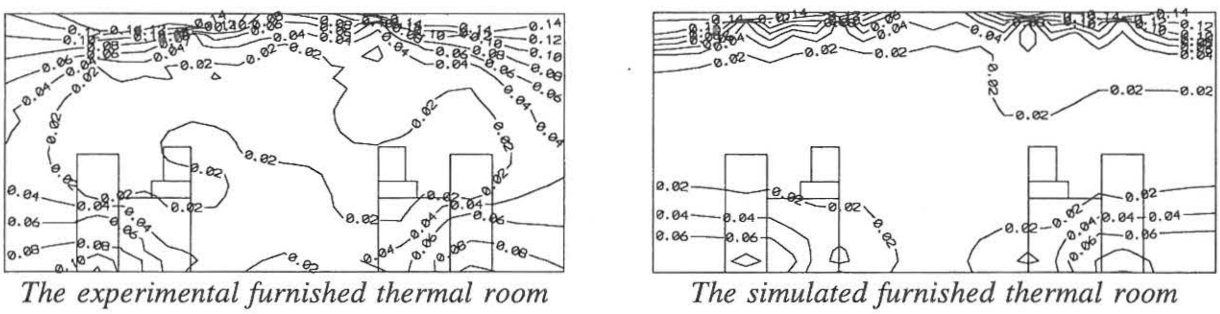


Figure 3.15 *The simulation of the physical set-up with office furniture with a thermal load.*

In the simulation of the furnished thermal room with two radial jets with swirl, the volume sources each have a total convective heat load of 40 W. This is 20 W less than the value used in the thermal simulation of the room with the 3-dimensional slot inlet in spite of that the experimental value per unit is 100 W in both cases. The low value is chosen because it creates the same Archimedes number, Ar, as in the experiment. The reason for the total convective heat load per unit being smaller in this case is, that only the convection part of the heat load is used in the simulation. In the room with the two radial jets with swirl the air movements in the occupied zone of the empty and in the isothermal furnished room are almost stagnant and by that a larger part of the heat load is emitted as radiation. Another reason is also the reduced air flow in the room (see section 2.2.1.3). The use of 40 W per unit (equal to a total convective heat load of 240 W) creates a temperature difference between the exhaust and the inlet of 6.2 K. This corresponds to an Ar of $2.68 \cdot 10^{-3}$ which is a little higher than the value found in the experiment (Ar equal to $2.60 \cdot 10^{-3}$). The deviation in Ar is found acceptable.

The investigations of the simulation with the furniture volume and the volume source are concerning the velocity level in the room, the velocity profiles through the room, the velocity decay at the ceiling, the length scale, the distance to the virtual origin, the individual constant of the diffuser and the maximum velocity in the occupied zone. At first, a comparison of the velocity level in the experimental furnished room and in the simulated furnished room is made. Figure 3.16 shows the velocity level in the two rooms.

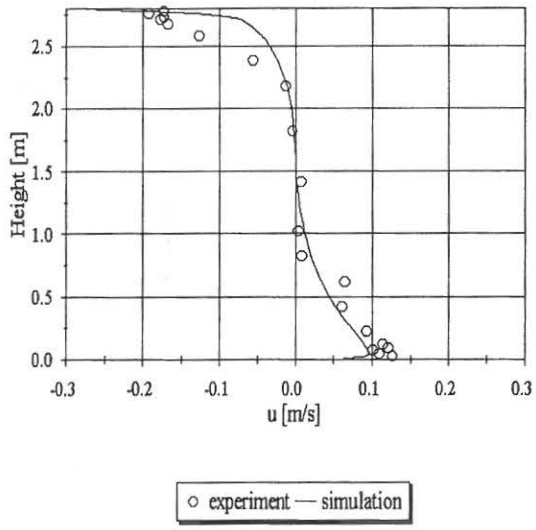


The experimental furnished thermal room *The simulated furnished thermal room*

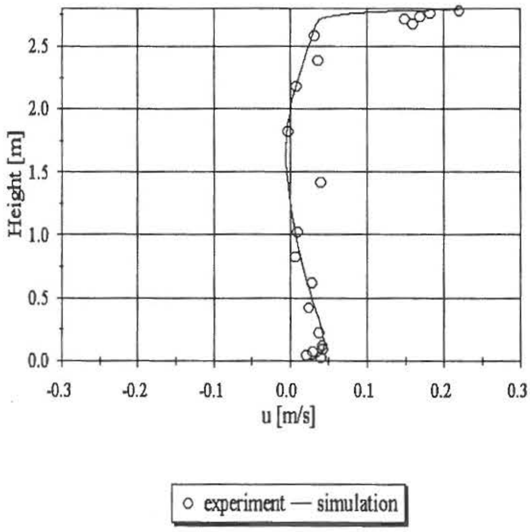
Figure 3.16 *The velocity level in the experimental and simulated furnished room with a thermal load.*

The comparison of the simulated furnished thermal room and the experimental furnished thermal room shows that the air flow in the upper part of the room is similar. At the end walls the velocity in the simulated room is lower than in the experimental room. In the middle of the room no particular difference occurs. The velocity level in the floor area of the experimental room is higher than in the simulated room. This was also found in the comparison of the two empty rooms (see figure 2.60 page 58) so it does not necessarily mean that the furniture volume together with the volume source is not suitable for representing the normal office furniture with a thermal load in this case.

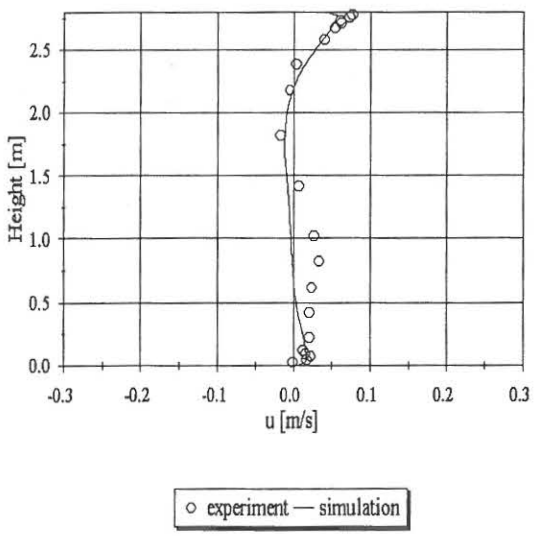
The simulation of the furnished room is investigated further by studying the velocity profiles through the room. The positive direction of the velocities is defined in figure 2.25 page 22.



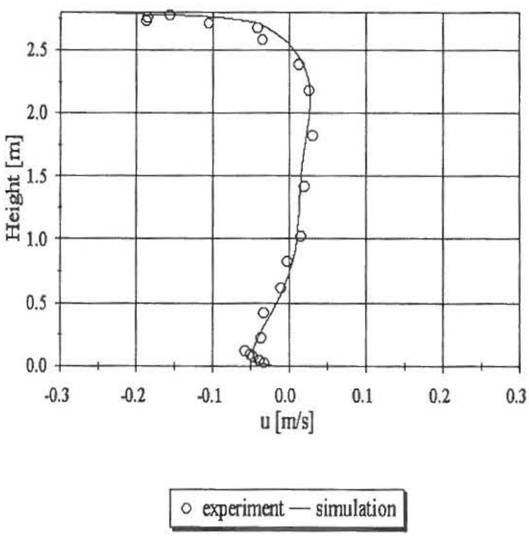
1.00 m from the end wall



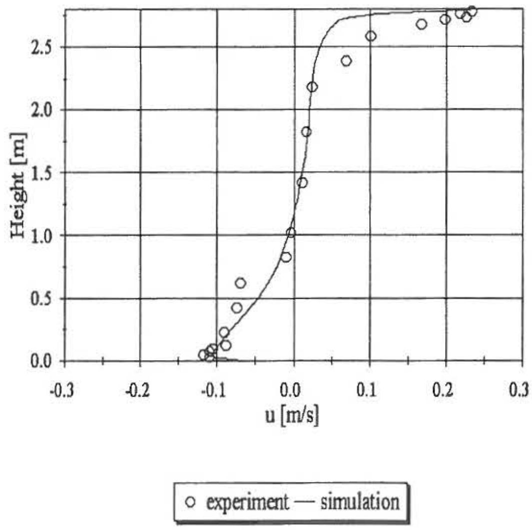
2.00 m from the end wall



3.00 m from the end wall



4.00 m from the end wall



5.00 m from the end wall

Figure 3.17 *The average velocity profiles measured 1.00, 2.00, 3.00, 4.00 and 5.00 m from the left end wall in the furnished room with the two radial jets with swirl. The diffusers are located 1.50 and 4.50 m from the left end wall.*

The velocity profiles through the room show similar results close to the ceiling where it is changing in which room the highest velocity is found. In the upper part of the room close to the end walls (1.00 and 5.00 m from the left end wall) it is found that the width of the jet is larger in the experiment than in the simulation. This could be caused by either the construction of the simulated inlet (see section 2.2.3.1) or by the use of the furniture volume together with the volume source. This will be investigated closer in the following. In the lower part of the room the velocities in the two rooms are almost concordant.

To investigate the difference observed in the ceiling area in the study of the velocity profiles through the room more closely, the velocity decay and the length scale are examined. The figure shows values from both sides of the inlets.

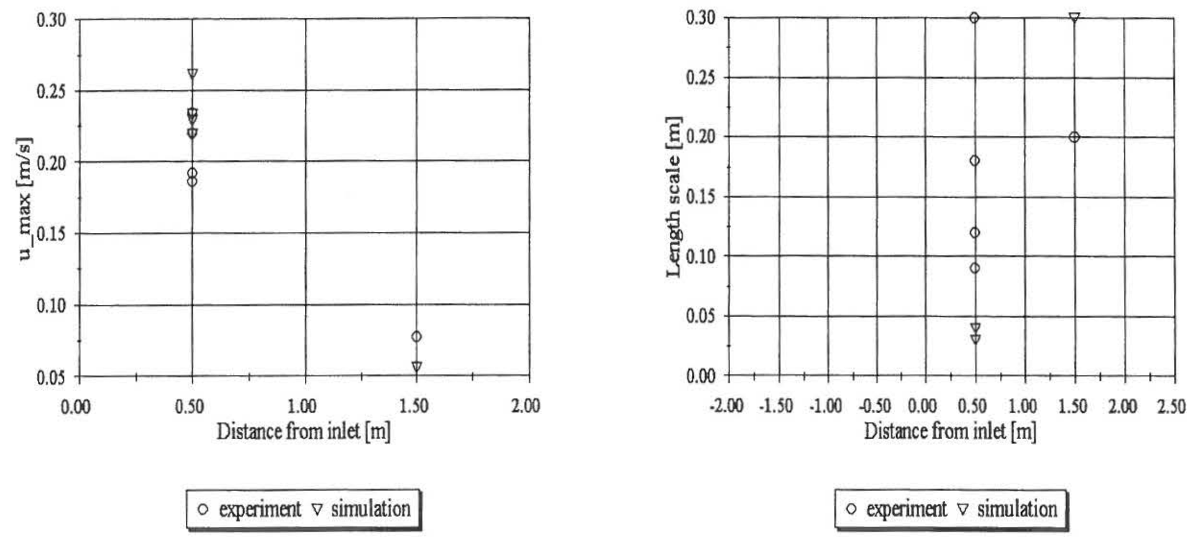


Figure 3.18 *The velocity decay under the ceiling to the left (u_{max} is the absolute maximum velocity at the ceiling) and the length scale, δ, to the right - both as a function of the distance from the inlet. The two radial jets with swirl are located 1.50 and 4.50 m from the left end wall.*

Figure 3.18 shows that the maximum velocity in the simulated room is a little higher than the measured velocity except in the middle of the room (1.50 m from the inlet). The study of the velocity decay indicates that the simulation with the furniture volume and the volume source is satisfying. The figure also shows that the length scale in the simulated room is smaller than in the experimental room. This was also to be expected from the investigation of the velocity profiles. To evaluate the effects of this deviation further, the distance to the virtual origin and the individual constant of the diffuser are examined.

The distance to the virtual origin, x_0, is found in figure 3.18 to the right where the regression line intersects with the x-axis. In the simulated furnished room x_0 is found to 0.35 m which is considerable lower than x_0 found in the experimental furnished room (1.75 m) but 0.35 m was also found in the empty room and in the isothermal case with office furniture so it is not necessarily the simulation of the furnished room that shows deviating results. The difference could be caused by the lower heat load in the simulated room so that the thermal forces does not affect the jet as strongly as in the experiemental room. The individual constant of the diffuser, K_{rs} is found from equation (2.3) page 31 and it is approximately 0.4 which also is the value found in the experimental room. Hereby, the furniture volume together with the volume source seems to be a suitable representation of the normal office furniture with a thermal load.

Finally, the maximum velocity in the occupied zone is investigated. In the simulation of the thermal furnished room with the 3-dimensional slot inlet the opposite result was found than in the corresponding experiment. Table 2.6 shows the maximum velocity in the occupied zone found in the experimental and the simulated furnished room.

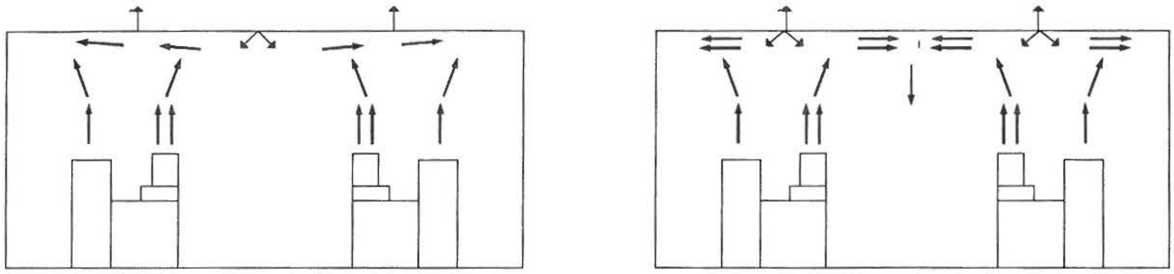
	Experiment		Simulation	
	empty room	furnished room	empty room	furnished room
u_{rm} [m/s]	0.015	0.127	0.012	0.106
$u_{rm}/u_{rm,0}$		8.47		8.83

Table 3.4 *The maximum velocity in the occupied zone found in the empty and the furnished room with a thermal load. The velocity in the furnished room, u_{rm}, is compared with the one found in the empty room, $u_{rm,0}$.*

The table shows that in both the experimental and the simulated furnished thermal room the maximum velocity in the occupied zone is increased considerably. The increase in velocity is almost identical in the two cases so on the basis of the investigations made of the simulation with the furniture volume together with the volume source it is found that this way to represent normal office furniture with a thermal load is satisfying.

The investigations of the thermal experiments and simulations have shown that in the room with the 3-dimensional slot inlet, the jet under the ceiling is affected by the normal office furniture with a thermal load. Opposite, in the room with the two radial jets with swirl it is found in the experiment that the jet becomes wider whereas no influence is found in the simulation. The influence on the jet at the ceiling is partly caused by the thermal conditions and partly by the normal office furniture. In the room with the 3-dimensional slot inlet K_p is halved compared with the empty room whereas in the room with the two radial jets with swirl, K_{rs} is identical to the value found in the empty room. In the occupied zone it is found in the experiment with the 3-dimensional slot inlet that the maximum velocity is decreased compared with the empty room. The reduced maximum velocity is caused by the thermal forces preventing the air from reaching the floor. In the simulation of the room with the 3-dimensional slot inlet and in both the experiment and the simulation of the room with the two radial jets with swirl it was found that the velocity increases. The latter result has also been found earlier /27/ and /30/. The increase in the maximum velocity in the occupied zone is largest in the room with the two radial jets with swirl and it is possibly because the air in the empty room is almost stagnant and by that the upwards directed flow created by the heat sources causes a larger change of the overall air movements in the room. The investigations have also shown that a furniture volume together with a volume source is an acceptable representation of the normal office furniture with a thermal load.

As indicated above, the two rooms show different response to the normal office furniture with a thermal load. This could be caused by the location of the heat sources compared with the location of the inlet. The thermal forces then affect the flow in the room differently in the two rooms which is indicated in figure 3.19.



3-dimensional slot inlet *Two radial jets with swirl*

Figure 3.19 *The thermal air movements over the heat sources in the thermal room with the 3-dimensional slot inlet (to the left) and in the thermal room with the two radial jets with swirl (to the right).*

The thermal forces in the room with the 3-dimensional slot inlet create an upwards moving air flow that meets the inlet jet at the ceiling with a flow in the opposite direction. This means that the individual constant of the diffuser is decreased and that the thermal flow over the heat sources prevents the air flow from reaching the floor. In the room with the two radial jets with swirl the thermal flow over the heat sources takes place almost directly under the inlets. Hereby, the thermal air flow supports the jet at the ceiling and more air is entrained and by this the width of the jet is increased (see figure 3.10 page 89).

It is concluded that the location of the heat sources compared with the location of the inlet is very important. If the heat sources were located differently in the two cases, for example in the middle of the room, another result would be found because the thermal air flow over the heat sources would then affect the jet under the ceiling differently and by that the air flow in the whole room.

4 Conclusion

In this thesis it has been investigated how normal office furniture influences the air movements in a mixing ventilated room. Both isothermal and thermal experiments and simulations form the basis of the investigations. The isothermal case is studied more closely than the thermal case and in consequence the conclusions are more supported. Further experiments and simulations must be made before final conclusions can be made.

In the isothermal case the experiments have been carried out with three different types of inlets: a 2-dimensional slot inlet, a 3-dimensional slot inlet and two radial jets with swirl. In the room with the 2-dimensional slot inlet three different set-ups with the same office furniture have been tested. The furniture is only located in the half of the room opposite the inlet where the maximum velocity in the occupied zone is to be found. The three situations with furniture are simulated 2-dimensionally. In the experiments in the room with the 3-dimensional slot inlet and in the room with the two radial jets with swirl only one set-up with normal office furniture has been tested in each room. A 3-dimensional simulation with the furniture volume is made in both cases .

The research procedure in the isothermal case has been:

- ① Measurements in the empty room.
- ② Measurements in the furnished room (five set-ups have been tested).
- ③ Simulation of the empty room where the inlet conditions are adjusted so that agreement with the air flow in the experimental empty room is achieved.
- ④ Simulation of the furnished room where a volume resistance is used instead of inserting the furniture in details. The volume resitance has a loss coefficient, f, that must be adjusted so that the simulation corresponds the experiment. This loss coefficient is determined so that the same value is valid in the five set-ups. A loss coefficient, f, equal to 0.5 m^{-1} is found suitable for the representation of normal office furniture (the furniture volume).
- ⑤ Further simulations are made with the furniture volume where the size and the location of the furniture volume are varied. Finally, the length of the room has been varied. These simulations have only been carried out in the room with the 2-dimensional slot inlet.
- ⑥ The results found in ②, ④ and ⑤ are used to create a method for the determination of the maximum velocity in the occupied zone of the furnished room. The maximum velocity in the furnished room is determined on the basis of the maximum velocity in the occupied zone of the empty room and the total length of the furniture in the main flow direction. Furthermore, the jet under the ceiling and the momentum flow through the room have been studied.

The investigations made in ⑥ show that the maximum velocity in the occupied zone is reduced by the furniture. It is found that the maximum velocity decreases when the total length of the furniture in the main flow direction increases for rooms with a length between 3.75 and 7.50 m. If the furniture is located outside the area of the maximum velocity or if the furniture is large, the reduction in the maximum velocity is insignificant.

The examinations of the jet under the ceiling show that the furniture does not affect the jet considerably so the jet is here undisturbed. If the furniture is very large and at the same time located in the area of the maximum velocity, some disturbance of the jet can be found. This large size of the furniture is unlikely in a normal office if the space requirements are maintained.

The study of the momentum flow through the room shows that the furniture reduces the momentum flow both at the ceiling and at the floor. This is caused by a deformation of the velocity profile and a reduction in the velocity level in the room. The reduction in the momentum flow is dependent on the relation between the size of the furniture and the length of the room. The reduction is decreased when the size of the furniture is small compared to the length of the room.

In the thermal case experiments have been carried out in both the room with the 3-dimensional slot inlet and in the room with the two radial jets with swirl. Only one set-up has been made in each room and in both cases the heat load was 600 W. The set-up in the two rooms is identical to the set-up in the isothermal case. The experiments have been simulated 3-dimensionally with the furniture volume and a volume heat source. The investigations of the thermal experiments and simulations are not so thorough as in the isothermal case because only two examples are present.

The research procedure in the thermal case has been:

① Measurements in the furnished room with a thermal load (two set-ups have been tested).

② Simulation of the furnished thermal room where the furniture volume is used together with a volume source with a total heat load.

③ The results found in ① and ② are studied. The maximum velocity in the occupied zone and the jet under the ceiling are compared.

The maximum velocity in the occupied zone of the furnished thermal room is decreased in the experiment with the 3-dimensional slot inlet, whereas the velocity is increased in the corresponding simulation. An increase in the velocity is also found in the experiment and the simulation of the furnished thermal room with the two radial jets with swirl. The increase in this case is much larger than in the simulated room with the 3-dimensional slot inlet. The low velocities in the room with the 3-dimensional slot inlet are caused by the thermal flow over the heat sources preventing the air from reaching the floor. In the room with the two radial jets with swirl the large increase in the velocity is caused by the almost stagnant air in the empty room. Hereby, the upwards directed flow created by the heat sources causes a large change of the overall air movements in the room. The changes in the maximum velocity in the occupied zone are partly caused by the furniture and partly by the thermal forces in the room.

The jet under the ceiling is affected by the furniture with a thermal load. In the room with the 3-dimensional slot inlet the velocity is decreased, and in the room with the two radial jets with swirl, the width of the jet is increased. These changes of the jet under the ceiling are partly caused by the furniture and partly by the thermal forces in the room. It has been indicated that the location of the heat sources could cause the different results in the influence of the jet under the ceiling.

From the investigations made in this thesis it can be concluded that normal office furniture with and without a thermal load affects the air movements in a room differently. In the isothermal case only the air movements in the lower part of the room are affected whereas in the thermal case the air movements in the whole room are affected. It has also been found that a volume resistance can represent normal office furniture and that an additional volume heat source can be used in the thermal case. This model is limited because the local flow field close to e.g. persons is not resolved in details.

The results found in the isothermal case are:

① the jet under the ceiling is insignificantly influenced

② the maximum velocity in the occupied zone is reduced. The reduction is dependent on the total length of the furniture in the main flow direction

③ the momentum flow through the room is reduced because of a deformation of the velocity profile and a reduction of the velocity level in the room. The reduction is dependent on the size of the room and the size of the furniture

The results found in the thermal case are:

① the jet under the ceiling is affected
② the velocity is decreased and the width of the jet is increased
③ the maximum velocity in the occupied zone is increased

It must be pointed out that maximum velocity in the occupied zone in certain isothermal caes may exceed the maximum velocity in the empty room, for instance where the air flow is strongly blocked by obstacles.

The isothermal case has been tested thoroughly in the case of normal office furniture, and the investigations of the results can be extended in other fields than the few chosen in this thesis. For example, the location of the furniture volume in the 3-dimensional simulations can be tested both in relation to the side walls and in relation to the end walls. In the thermal case only two experiments and the corresponding simulations have been tested and in this field further investigations have to be made. Here, an interesting parameter is the Archimedes number and, like in the isothermal investigations, the location of the heat sources could be varied.

The field of the influence of furniture or other obstacles on the air movements in a room is important to continue the investigations, because by that a better understanding of the complex air movements in a room is achieved. It will make the ventilation designers capable of creating a better indoor climate which will be of benefit.

Appendix A

The purpose of this appendix is to prove that the two hanging lamps in the room with the 2-dimensional slot inlet (see figure 2.2 page 6) only have a negligible influence on the inlet jet. In this way they can be left out in the drawings and especially in the simulations. The influence on the jet under the ceiling is investigated by comparing the velocity decay in the room without the lamps with the velocity decay in the room with the lamps. Measurements in the room with the 2-dimensional slot inlet without the lamps have been made on other locations than the measurements in this thesis. Figure A.1 shows the maximum velocity at the ceiling, u_{max}, as a function of the distance from the inlet.

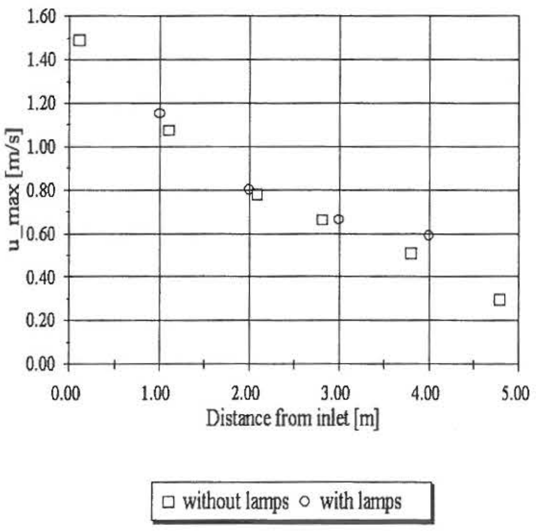


Figure A.1 *The velocity decay in the room with and without the hanging lamps.*

The figure shows that the velocity decay in the two rooms is similar. It is only farthest away from the inlet that some difference occurs. This difference is caused by a not completely 2-dimensional flow at the ceiling in the room with the lamps (see section 2.1.1.2 page 7). Hereby, the simulations can be made without the hanging lamps.

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